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THE OPTICAL AND PSYCHOLOGICAL PRINCIPLES INVOLVED IN THE INTERPRETATION OF THE SO-CALLED CANALS OF *MARS*

By SIMON NEWCOMB

The features of the planet *Mars* as described by Schiaparelli, Lowell, and other observers are so remarkable that the question of their interpretation is of great interest. The divergence between the descriptions and delineations of these features emanating from different observers is well known, and seems scarcely normal. Accepting, as we should, the general principle that what is seen by a single practiced observer under the most favorable conditions affords evidence which completely outweighs that of less favored observers, we must still admit that absolute inconsistency between the two should not be found. The details successively added under improving conditions may not be inconsistent with a rational interpretation of what was previously seen. It has been emphasized by Williams and also by Lowell that an observer with the widest experience in seeing only one class of features may fail in seeing those of another class. Even if this contention is correct, it does not seem to afford a completely satisfactory view of the case.

The optical and psychological principles involved in the interpre-

tation have been investigated and set forth by Lowell in his publications and researches relating to *Mars*. But it seems to me that there still remains something to be done in this direction; and the present paper is the outcome of an attempt to investigate the optical and psychological causes on which depends the judgment of an observer in scrutinizing faint and difficult features on the surface of a planet. While the writer cannot pretend to have solved all the difficulties of interpretation, and may have brought out more than he has solved, he hopes to do something toward laying a basis for further progress.

Two sets of principles come into play, one optical, the other psychological. Under the first head are included all the causes which affect the formation of an image on the retina of the eye; under the second the causes which affect the observer's perception of this image. The principal agencies which come into play in the first class are the atmosphere, the instrument, and the eye. What I have done relates mainly to the instrument, the aberration of the eye being well understood, and involving no principles not at play in the instrument.

A. OPTICAL PRINCIPLES

Notwithstanding the great volume of literature relating to the telescope, I am unable to refer to any one source where the effects of the secondary aberration of an achromatic lens, and the primary aberration of the eye, are stated in a form to be easily applied to this special question. The complete development of the subject would be foreign to the purpose of the present paper, but it seems necessary to summarize the data and formulae in such a way that they can be readily applied. To do this I use the following notation for the quantities which come into play in the working of the ordinary two-lens achromatic objective:

p and p', the geometric power of the objective, for which I take the sum of the reciprocals of the radii of curvature. The accented quantities throughout are those which relate to the flint lens.

k, the ratio $p' \div p$ of the geometric power of the flint, taken as positive, to that of the crown.

$\nu = \mu - 1$, μ being the index of refraction.

a, linear radius of aperture of objective.

f, focal length of objective for any ray. Since f is in general

different for different rays, we assume a special value l for the focus to which the eyepiece is adjusted for sharp vision, and put

$$l-f=r\,.$$

Passing the focal plane P through this adopted focus, r is then the distance of the true focus of any ray from the plane P.

ρ, linear radius of the circle of aberration formed by the light of any ray converging from the objective upon the plane P. For a ray coming to a focus on P we shall have $\rho=0$.

s, the angular radius of the circle of aberration upon P, as seen from the objective.

It may be remarked that a rigorous determination of the focal length and of the spherical aberration is unnecessary. We assume the latter to be perfectly corrected, and an approximate numerical value of the same focal length is sufficient for our purpose.

The focal length for any ray is given by the equation

$$\frac{1}{f}=\nu p+\nu' p'=p(\nu-k\nu')\,. \tag{1}$$

We may call k the achromatizing factor; p and q are constants for the telescope, and k is so taken that the focal length shall be the same for some two rays, which we may designate by the suffixes 1 and 2. We shall then have, to determine k,

$$k\nu'_1-\nu_1=k\nu'_2-\nu_2\,,$$

which gives

$$k=\frac{\nu_1-\nu_2}{\nu'_1-\nu'_2}. \tag{2}$$

The exact value of k, like that of p and q, is a function of the curvatures of the lenses. Regarding it as given, the focal length for each separate ray is determined by the equation (1).

The linear radius of the circle of aberration upon the plane P is given by the equation

$$\frac{\rho}{a}=\frac{r}{f}=pr(\nu-k\nu')\,, \tag{3}$$

and the corresponding angular value s of this radius is given by

$$s=\frac{\rho}{l}=\frac{a}{l}\,\frac{r}{f}\,. \tag{4}$$

From this equation we may compute the value s for the different rays in any telescope for which the constants p and q are given, the in-

dexes of refraction of the glasses being also supposed known. All accurate determinations of the indexes for crown and flint glass as ordinarily used show that the properties of these two glasses are so related that for a given ratio of focal length to aperture, and for a given chromatic correction, the values of s are practically the same for all combinations of such glasses hitherto investigated. Of course, the special kinds of glass made by the well-known Jena manufacturers are here to be excepted; but such glasses have not yet been extensively applied in observations on the planets. It is therefore not necessary to inquire into the special properties of the glasses used in this or that telescope. The indexes of any combination of flint and crown will answer the present purpose. We take for our purpose the objective of the Mount Hamilton 36-inch equatorial, the refractions of which were very carefully determined by Professor Charles S. Hastings. The results which we have used are shown in the table next following.

I do not know the precise value of the achromatizing factor used in the construction of this telescope, nor is it important for our purpose to know it. It will suffice to use a factor having as nearly as may be the best value for the visual field. This value cannot be definitely fixed, because from the brightest part of the spectrum the luminosity fades off more rapidly toward the red than toward the blue. It follows that the combination which will bring the greater part of the light into the smallest space is not exactly that which will produce the brightest stellar image at the central point. I have assumed $k = 0.508$ to be as good as any, but our conclusions will not be altered by any admissible change in this factor.

The first column of the table designates the rays which Professor Hastings measured. The first two columns of numbers give ν and ν' for the rays in the brightest part of the spectrum from C to F. The third of these has no designation other than its wave-length, which is 5614.

We next have $\nu - k\nu'$, which is the inverse focal length in terms of the inverse geometric power of the crown lens. The maximum value of this quantity falls, as it should, between D and the ray next below it, and is not far from 0.194636. This would be the focal setting to secure the sharpest central image of a star. But, practically, a better focus to secure the minimum dispersion will probably correspond to

the number 0.194630. Taking this value, we have, by subtraction, the values of

$$\Delta=\frac{1}{l}-\frac{1}{l+r}=\frac{r}{lf},$$

found in the fourth column of numbers.

We have to derive from Δ an expression for the radius of the circle of aberration. Comparing (4) and (5), and putting $\frac{1}{l}=0.1946$, we find

$$s=5.14\frac{a}{l}\Delta\,.$$

Since s contains as a factor the ratio of the semi-aperture of the telescope to the focal length, it will, in a given telescope, be proportional to the breadth of the aperture actually used, and may be reduced indefinitely by diminishing this aperture. But apart from the drawback of cutting off the light, reduction of the aperture increases the defect arising from diffraction, of which we have taken no account in the preceding geometrical derivation. It is not likely that any result can be secured better than the one we should obtain by assuming a ratio of aperture to focal length of 1:20, which gives $s=0.1280$. Multiplying by the seconds in radius, we find that the minimum value of s which we can reasonably expect to secure may be expressed with all necessary precision by the formula

$$s=26400''\Delta\,.$$

The values of s thus derived are given in the last column of the table.

Ray	ν	ν'	$\frac{1}{f}$	Δ	s
C...........	0.511565	0.624043	0.194551	$-79\div10$	2.0
D...........	.514164	.628994	.194635	$+5\div10$	0.12
λ5614........	.515474	.631578	.194632	$+2\div10$	0.05
E...........	.517440	.635476	.194618	$-12\div10$	0.30
F...........	.520316	.641340	.194515	$-115\div10$	2.9

Without going into details of computation, it follows from these numbers that by no focal setting can all the light contained between the second and third lines, or between wave-lengths λ 5894 and λ 5614, a range of 280 tenth-meters, be brought within an aberration circle the radius of which is much less than 0.″10, or the diameter much less than 0.″20. If there is a possibility of the image being made materially smaller, we may regard it as certain that the effect of

atmospheric softening and of diffraction will be to enlarge the image beyond this radius. If we set the focus so as to secure a brighter central point, we increase the radius for the rays on each side, and vice versa. The range of wave-lengths between the lines C and E is 0.1290, and extends from the dark red to the fainter portion of the green, excluding the blue entirely. Were all the light outside these limits brought in and distributed so as to form a uniform spectrum, I conceive that it would be as bright as if the light of the brighter portion were spread between the limits C and E. I therefore conclude that *in using the best refracting telescope under the best conditions we cannot expect to bring more than one-fourth the light within a circle of radius 0".10, three-fourths being distributed outside this circle.*

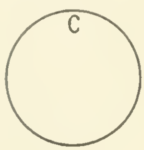

FIG. 1.

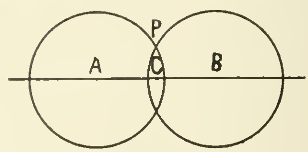

FIG. 2.

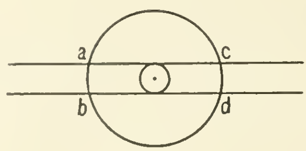

FIG. 3.

The injurious effect of this dispersed light may be lessened by the use of a suitable absorbing screen, which is among the devices used at the Lowell Observatory. I do not know how successful this device has proved in bettering the definition, but it seems quite certain that it could not be so applied to bring the bright central image within the limit of 0".10, and, in fact, would have to be wonderfully adapted to the requirements to bring it even to this limit.

We have next to consider the respective effects of this aberration upon a star and upon a line. In the former case the light of each ray being spread into a circle of radius s, the surface brilliancy of the disk produced by the light of any ray is inversely proportional to s. It therefore rapidly diminishes as we go out from the central point, which accounts for the fact of a companion star being visible at a distance of less than 0".1 from the central star.

A study of Figs. 1, 2, and 3 will show that when a line is observed

the result is materially different. In Fig. 1 let the central point be that of a stellar image, and let the circle be that of aberration for a ray of any wave-length. Then, as just stated, the intensity of the illumination by this ray over the entire surface will be proportional to the inverse square of the radius, and directly as the intensity of the ray. Since, as we approach the center of intensity, the light increases, while the radius diminishes, the illumination increases with greater and greater rapidity, so that the central point is distinctly marked.

In Fig. 2 let the horizontal line represent a line of light on the focal plane, as it would be if perfectly sharp. Let us next inquire into the amount of the illumination at a point P, at a perpendicular distance C from the line as produced by aberration. Take the points A and B at such a distance that $AP = PE = S$, and draw a circle around A and B through P. The point P, instead of being dark, will then be illuminated by all the C-light emanating from the segment AB of the line. Without going over the process of geometric and algebraic reasoning which would be necessary to give the conclusion a precise form, it will be clear enough that the illumination at P would be proportionately brighter than if the light were dispersed only from the center C.

In Fig. 3 let the lines AC and BD represent a perfectly dark strip observed on a bright background. From any point in the central line of the strip describe an aberration circle tangent to the two boundaries. It is evident that this point, and therefore the entire central line, will be black only with respect to the rays, say R, whose radius S of aberration is less than half the breadth of the line. For, to fix the ideas, let the breadth be $0''.20$. Then in the case of the hypothetical telescope adjustment which we have assumed, the central line would be darkened only to an extent not much greater than the total light R. At either edge of the strip, the brightness will be one-half that of the surface on each side, plus the light dispersed across the surface. The darkening would be distributed over a belt several times that of the actual belt, no definite limit being assignable, since it would fade off indefinitely in each direction. All that we can say with precision is that the total amount of darkening or abstraction of light would be equivalent to that produced by the central black band.

It is, of course, open to anyone to define the illumination, or the

amount of darkening, by algebraic formulae. But such formulae would have to contain as an unknown quantity the aperture of the objective, and to be complete should also include the defects of diffraction and atmospheric diffusion. The uncertainties thus arising are such that I conceive no practical gain would accrue by aiming at algebraic precision in the expression of the illumination in detail.

B. PSYCHOLOGICAL PRINCIPLES

Notwithstanding the volume of investigation on the psychology of vision, that branch of the subject which relates to accuracy of conception and estimate is, so far as the writer is aware, an almost virgin field. Two distinct processes are involved in vision. One is the conscious stimulus of the optical nerves by light, the other the perception by the mind of a real or supposed object indicated by such stimulus. The most remarkable property of vision is that it does not consist merely in taking account of the sensation, but is occupied almost entirely with the perceptive act, in which the sensation is dropped out of consciousness. Crude indeed would be a form of vision which ignored all but sensation. I shall use the term *visual inference* to describe the act by which the mind unconsciously draws conclusions as to an observed object from the image formed by its light on the retina. A fundamental property of this form of inference is that it comprises not only *seeing*, in the ordinary sense, but a rational interpretation or conclusion based on previous experience of what is seen.

This general proposition will be made clear by an example. Suppose oneself looking at a white line on a black background. We know from our experience in looking at a gas-lamp at night, or at a bright star, or even from a consideration of the refraction of the lenses of the eye, that the light emanating from a bright point is spread over a surface of several minutes' radius, which commonly increases with the age of the individual. Regarding it as a circle it it has not in any case a definite size, the light shading off gradually from the center outward. It follows that, when we look at a bright line, the image formed on the retina, even in the best eyes, must be 2′ or 3′ in breadth, howsoever thin the actual line may be.

But as a matter of fact, experience leads us to perceive only what

we should call a line, though we know rationally that it must have a sensible thickness. In other words, by the process of visual inference the eye does not perceive the line as it is actually pictured on the retina, but unconsciously introduces a correction based on general experience as to the geometrical form of the object which produces the image. It not only corrects the defects of the eye, but, by long experience, does this so completely that the defects pass in a large measure unperceived.

In this process we have a possible fruitful source of error of vision which, instead of being corrected by experience, tends to be strengthened by it. A mind accustomed to dealing with objects the correct perception of which depends mainly on visual inference, is naturally prone to extend that inference to cases where the conclusion would be illusory. Having this in mind, we see that observers trained in different ways may depict the same object very differently.

The process in question naturally plays a more important part as the object observed approaches the limit of visibility. If we can barely see an object in the darkness, we cannot distinguish its exact outline or character. Visual inference here comes in and assists the judgment as to the nature and character of the object. This may be the case even when the illumination is sufficient to render the object plainly visible, if only the mind is in a restful state. The fantastic character of the forms which may be seen in the coals of a fire by one sitting before it is well known. This example is not, however, pertinent to our present theme and is mentioned only as an additional illustration of this form of inference. As it is not possible within the limits of the present paper to discuss the subject in its generality, I shall limit myself to the special cases of lines approaching the limit of visibility.

As bearing on the question, I have made a number of experiments on the visibility and visual interpretation of dark lines on a white background. They differ from the similar ones made by Lowell in that, instead of taking the sky as a background and a distant wire as the dark line, I have used lines drawn with ink on paper, the latter being placed in a window and observed by transmitted light. This system was adopted, not only for convenience, but because the conditions in this way approach more nearly to those of actual observa-

tion on the disk of a planet, where the apparent background is not formed by the uniform blue light of the sky, but by a more or less mottled surface, and the lines are affected by atmospheric dispersion and telescopic aberration. Another point of difference was that, instead of making degrees of visibility, especially the *minimum visibile*, the main object, I sought to investigate the nature and limits of visual inference.

It is unnecessary to describe the experiments in detail, because they can be repeated in unending variety and by improved methods with great ease by anyone who desires to do so. The only particulars necessary are these. The lines were ruled lines about 0.7 mm in thickness, the length of all the lines being about 30 cm. One was continuous, others were broken at regular intervals by spaces 1 cm in length. There were also short lines from 1 cm in length upward. The lines being observed by transmitted light were not black, but gray and diffuse, thus corresponding more nearly to the telescopic vision than would black lines.

At a distance of 10 meters all the lines looked continuous and uniform. As the distance was diminished, the perception of the gaps did not come on suddenly, but by gradual steps. The first impression was that the lines were affected by irregularities in the form of thicker portions or blotches. The discontinuities were perceived gradually as the distance was diminished. The question thus suggested may be approached in this way. Consider or draw a line of considerable length so fine as to approach the limit of visibility. A segment L of this line can be taken so short as to be invisible. To avoid the question of an absolute *minimum visibile*, we may, if we choose, take a length L so short as to be perceived only with a minute intensity I. Now take from the whole line a segment of the length L; with what intensity will the absence of this segment be perceived? If we regard this impression as negative, we may say that the absence of this segment will be unperceived and that the mind will continue to perceive the negative impression. It follows that discontinuous portions of a line may be integrated into a continuous line.

Carefully testing this principle, the result might be stated in this way. The discontinuities were seen as such only at the distance at which the length L became certainly visible. At distances a little

greater than this there was a certain indefiniteness which made it impossible to decide whether a discontinuous line or one of varying thickness in different parts was being observed. The distance had to be increased only by a moderate fraction of its whole amount to render the perception of the line absolutely continuous. It seems to me that this principle affords as precise a statement as can be made of the conditions under which the process of visual integration, or perception of a discontinuous collection of objects as continuous, will take place.

From what has been said we should regard the process of visual inference in this case as quite legitimate. Any error of judgment into which it leads us admits of rational correction, and such correction should be applied just as in the case of optical illusions or other sources of error. But the most surprising result of the few experiments I made was that the process assumed a form which, believing my visual habits to be at least as free from error as those of the ordinarily well-trained observer, was entirely unanticipated. When looking at the lines without exactly knowing where and what they were, I found that in one case what was faintly judged to be a continuous line up and down the paper was really a short line with a faint shade below it, which by visual inference was merged into the line, and led to the acceptance of its continuity across the paper. But a greater surprise was felt when a paper which I knew to have no visible lines upon it was in the window, and I fancied that I saw a system of continuous lines similar to that which I had been observing. So strong was this impression that, had I not known that the phenomenon was an illusion, I might have described or delineated the lines without any suspicion of their unreality. Going forward to see what caused the illusion, I found it due to an irregular shading of the tissue of the paper as seen by the transmitted light. The minutely darker ill-defined regions which were scattered all over the paper were integrated into lines like those I had been observing. I have understood that something of this sort has been noticed by others, but I was disposed to look upon the matter lightly until I experienced the illusions myself. Mr. Maunder's elaborate experiments in this direction, as described in the *Monthly Notices*, *R. A. S.* (**63**, 488, 1903), which were made upon schoolboys, have seemed to me open to question for two reasons. In the first place, experienced observers would

have been preferable to schoolboys; in the next place, drawings with a pencil were trusted, without (it would seem) there being any test by description, thus leaving a doubt, when a line was drawn with the pencil, whether it was anything more than an effort to represent a more or less indefinite shade by the aid of the pencil. It seems to me that we have here a very interesting field in which the best astronomical observers might well experiment upon each other by placing in a window a number of such papers, some with barely visible lines and others without, and determining the degree of certainty with which the two could be differentiated at various distances.

Through the courtesy of Professors E. C. and W. H. Pickering, and S. I. Bailey, the author is enabled to present the result of an experiment of this kind, which seems not devoid of interest. Besides lines drawn upon paper, observations on which seemed to confirm the general principle already suggested, a circular disk was prepared with light shadings, bearing a faint resemblance to what might be supposed to exist on *Mars*, but which did not contain any canal system of the kind commonly seen. This disk is reproduced on a reduced scale with sufficient precision in Plate I. Its breadth and distance were arranged so as to correspond to the apparent disk of *Mars* under the usual magnifying power. The markings were then drawn by Professors W. H. Pickering and Bailey, with the results shown in Plate II. Neither was made acquainted with the actual nature of the figures until after the latter had been made. It seems unnecessary to enter into any details of the conclusions to be drawn from a comparison of the original with the reproduction, beyond the remark that they seem to be affected by practice. Professor Pickering was an experienced observer of the canals of *Mars*, while Professor Bailey, though occasionally looking at *Mars*, had not made so long a study of the planet.

Additional sketches of the wash-drawing were subsequently made by Professor E. E. Barnard and Mr. Philip Fox of the Yerkes Observatory, from a distance of 96 feet. They had not seen the original from a less distance at the time their sketches were made. With their permission these sketches, which were made very carefully, and which resemble each other very closely, are also reproduced here. (Plate III.)

C. POSSIBLE INTERPRETATION OF THE CANALS OF *MARS*

Our next step is to apply the preceding result to the interpretation of the markings on *Mars*, specially of the canal system. Here at the outset we must guard against the error of considering this whole system as something which must stand or fall as a unit. Some of the markings which it has become the custom to designate by the term "canal" are seen in substantially the same position by so many observers that no question can be raised as to their subjective reality. In fact, several of them have been photographed. It is also to be considered that, as a general rule, the more practiced the observers, the more of these objects they see. But even admitting the subjective reality of them all, the considerations already adduced show that there is still room for doubt as to their interpretation, when we include the whole system of about 400 lines definitely catalogued by Lowell and his observers. It is one thing to say that the whole system of fainter canals is an illusion, and quite another thing to say that its objective reality may be very different from the subjective appearance.

The present discussion of the subject will be based almost entirely on the work of the Lowell Observatory. The excellence of the instrument and of the atmospheric conditions do not form the only justification for this selection. The unequaled continuity of the observations, the care with which the minutest details were looked for, and the generally critical character of their entire discussion, add to the force given by the favorable conditions.

We first remark that, at the distance of *Mars* at various oppositions, one second of arc will commonly be subtended by a linear distance on the face of the planet varying from 200 to 300 miles (320 to 480 km). If the opposition occurred absolutely at the perihelion, the equivalent might be as small as 175 miles (282 km). But the occasions on which it will fall below 200 are rare, while approximation to 300 must be the general rule, owing to the brevity of the period near an opposition when the distance will approach its minimum. The figure 200 miles or 320 km will therefore correspond to the most favorable ordinary case; and we shall for simplicity take it as the basis of computation.

Now, conceive an absolutely black line on *Mars*, of indefinite

length, and of a breadth of 3 or 4 miles (5 or 6 km). The angular geometric breadth of the strip may be $0''.01$ to $0''.02$. From what has been shown, and is elucidated in Fig. 3, it will be seen that the image of this line in the best terrestrial refracting telescope will not be black in any part, but will be spread out into a band of which the darkest part will be $0''.2$ broad, bordered by a yet wider shade. It follows that even on the central line of the band, the actual amount of the darkening will be that produced by taking away about one-tenth or less of the light of the surrounding brighter regions of the disk. In other words, instead of a black line $0''.02$ broad, we have a faint shade from 10 to 20 times as broad. In linear measure on the planet the apparent band will be 40 miles in breadth and upward, instead of 3 or 4. This spread of the darkness will necessarily diminish its visibility.

The question of the visibility of such a band is a difficult one, because no tests of visibility derived from comparatively unpracticed eyes would apply to the experienced observer. It would, in fact, be almost impossible to estimate the *minimum visibile*, but for the observations bearing on the case by Lowell himself. He found that a wire projected on the sky vanished from sight with increasing distance only when its breadth subtended a diameter less than $0''.69$. Another datum is offered by what I believe is an established fact of photometry, that upon a uniformly illuminated surface of the best brightness a change of 1 per cent. of the light is perceptible.

The data, however, cannot lead us to a definite conclusion, because, in order that a shade may be visible, it must have a certain breadth. From observation and reasoning which I need not detail I should regard several minutes as the minimum breadth necessary for a 1 per cent. shade to be visible. It goes without saying that the breadth of $0''.69$ is visible only when black and when seen with perfect sharpness. If the blackness is spread out into a band by aberration, how much must the breadth of the wire be increased for a given breadth of band? It may be remarked that, if the breadth is multiplied 100-fold, we shall have a limit of visibility in a broad band indicated by the second principle just cited. But the breadth of the band would then be only $69''$, while from the rude observations I have made it may be inferred that the breadth of the shade when thus spread out would have to be

multiplied four or five times before becoming visible to an eye which could see it when sharply defined.

This statement presupposes that the bright background is perfectly uniform. This is not the case with *Mars*, and there is no doubt that the amount of the blackness for the *minimum visibile* would have to be multiplied several times on account of the variety of shading in the visible disk of the planet. To spread a band of $0''.2$ in breadth to $5'$ would require a magnification of 1500. I doubt if anything like this power could be advantageously applied. With a power of 500 the apparent breadth would be $1'\ 40''$.

My observations lead to the conclusion that on a quite uniform background this breadth of darkening will be visible, but that, if the background is in any way mottled, the mottling will be combined with the band in such a way that the judgment of the breadth may be quite illusory. If two objects just below the *minimum visibile* are combined, the combination may be visible as a single object; but the subjective effect may be very different from the objective reality. Only the roughest estimates are possible in the case; and I conceive that, subject to this drawback, although a perfectly black line 3 miles (5 km) in breadth might be visible on *Mars* if the surface of the planet were perfectly uniform, the breadth would probably have to be increased to 8 or 10 miles (13 or 16 km) clearly to differentiate the line from the markings in its neighborhood.

But it cannot be supposed that the canal system is absolutely black in color. Whatever its nature, we must suppose that its albedo is half or more of that of the surrounding regions of the planet. We must therefore, on this hypothesis, double the actual breadth. My conclusion is that the actual breadth of the narrowest visible canals on *Mars* must exceed 10 miles (16 km), and may be as great as 20 miles (32 km). Adding the border of 20 miles on each side necessarily produced by aberration, diffraction, and softening, the apparent breadth in the telescope and on the retina would be 50 miles (80 km) and upward.

This result differs widely from that of Mr. Lowell, who estimates 2 or 3 miles as the breadth of the narrower canals.[1] The source of the deviation of my result from his is quite simple. He compares the

[1] *Mars and Its Canals*, p. 182.

canal with a wire seen against a sky and therefore perfectly black. He also implies the image of this black line, about 0″.01 in minimum thickness, to be perfectly sharp on a uniform background. Increase its apparent breadth from this limit up to the diameter of the aberration circle in the best telescope, and suppose a half-blackness, and we shall have to multiply this breadth by perhaps 5 or 10 to correspond to the different hypothetical conditions. It is not necessary, however, to insist on the actual breadth of the narrowest line, because, whatever it may be, it will on the retina be increased by aberration, no matter how narrow the objective reality.

Let us now consider the entire system of 398 canals named and catalogued in the *Annals* of the Lowell Observatory.[1] It seems that 2000 miles is the common length of a canal, while many exceed 2500. Assuming 400 canals of a mean length of 1500 miles (2400 km), let us compute the area which the entire system will subtend on the retina of the terrestrial eye with the aid of the best refracting telescope.

The area of a mean canal in square miles will be

$$400 \times 1500 \times \text{Breadth} = 600{,}000 \times \text{Breadth}.$$

Then, taking in succession (1) a mean actual breadth on the planet of 7 miles as assigned by Lowell; (2) a mean of 15 miles, which, if my reasoning is correct, must be nearer the truth, in view of the canals not being black; (3) an enlargement of 40 miles by aberration, etc.—we shall have the results:

(1) Canals black: objective area, 4,200,000 square miles.
(2) Canals half-tone: objective area, 9,000,000 square miles.
(3) Canals enlarged: apparent area, 33,000,000, square miles.

The actual surface of *Mars* is about 55,000,000 square miles. We conclude:

Making due allowance for the aberration of the best achromatic telescope, the total area of the entire system of 400 canals, as depicted on the retina of the terrestrial eye, can scarcely fall much below one-half the total area of the planet, and may be greater. In fact, were all the canals on the disk visible simultaneously, it would be difficult to establish their reality, because several canals in the same neighborhood would interfere with each other's visibility. But it is understood

[1] Vol. III, pp. 268–277.

that such is not the case. Many of the fainter canals are variable and visible only occasionally. The preceding computations therefore give rather the total part of the surface that may be covered by the canal system than the actual area of the system as seen at any one time. Although these results may weaken the probability of the reality of the entire canal system, it does not disprove its possibility. In fact, it is quite consistent with Lowell's fundamental explanation of the phenomena. At the same time, it shows how wide is the possible field of interpretation, and explains the difficulty which many observers have encountered in tracing the canals. So complex a network within a disk only 20″ in diameter could not but be interpreted largely according to the experience and habits of the observer.

Although in this discussion the writer has not questioned the subjective reality of the canal system, he cannot but feel that the proof of its objective reality is incomplete until the observers of the system investigate the processes of visual inference in their own eyes. This involves no serious difficulty, being little more than an extension of the rude experiments described in the present paper. The experiments should be made by an independent agent preparing drawings, representing on sheets of white paper forms similar to those which might be supposed to prevail on the surface of *Mars*, in as great a variety as possible. These forms should then be studied by the observers without an advance knowledge of the details of each, and conclusions as to the nature of each drawing, and its resemblance to the Martian canal system, should be recorded by drawings and description. Then leaving a priori probabilities aside, the a posteriori probability would be in favor of the drawings which, in the opinion of the observer, most nearly resemble what he has been accustomed to see on *Mars*.

WASHINGTON
May, 1907

ARC SPECTRA UNDER HEAVY PRESSURE

By W. J. HUMPHREYS

The effects, discovered several years ago, of pressure of 10 to 12 atmospheres on arc spectra[1] indicated that results of some value might be found by examining spectra produced under much greater pressures. At that time higher pressures could not be obtained, but during the spring of 1906 I secured, with specially constructed apparatus, nearly two hundred spectrogram negatives, each 20 inches (50 cm) long, taken at pressures of 42, 69, and 101 atmospheres; to these some twenty supplementary ones have recently been added.

More than one hundred of these spectrograms have been selected and studied, only those being used that were taken when all parts of the apparatus were in careful adjustment, that had lines satisfactorily measurable, and that were above suspicion of accidental displacements during exposure.

A Rowland concave grating of 14,438 lines per inch (568 per mm) and 21.5 feet (6.5 m) focal length was used, and nearly all the negatives were taken in the second- and third-order spectra. The pressures were obtained by forcing air with a four-stage Norwalk compressor into a forged-steel bottle that contained the arc, and read by Crosby gauges, afterward tested by the Bureau of Standards and found to be substantially correct.

During each exposure the pressure was maintained practically constant by having the space about the arc in open communication, through a steel tube, with the compressor which was kept running with its blow-off valve properly set. The pump, which ran very smoothly, and the spectroscope were both located on basement floors, but in different rooms, and so far separated, about 50 feet (15 m), that no disturbance of the spectrum lines could be detected, though it was carefully searched for both visually and photographically. This freedom from disturbance probably was due in part to the fact that neither instrument was mounted on ground piers, and that there was nowhere any solid connection between them.

[1] Humphreys and Mohler, *Astrophysical Journal* **3**, 114, 1896; Humphreys, *ibid.*, **4**, 249, 1896 and **6**, 169, 1897.

The arc was produced by a 220-volt direct current of usually about 15 amperes. With this particular voltage, the highest easily available, it was not possible to maintain a satisfactory arc between fixed electrodes at the pressures used, and therefore one of the poles was rotated. This part of the apparatus is described on pages 36 to 40 in this number. The rotating pole was always the anode, and in nearly all cases consisted of carbon. The fixed pole was either carbon or a metal rod, depending on the element under examination. Commercial arc-light carbons, with iron, titanium, calcium, aluminium, and a few other impurities, gave good results, as did also such carbons after being soaked in salts of certain elements. Excellent results were likewise gotten with metal rods or blocks of iron, chrome iron, self-hardening steel (iron, chromium, manganese), brass, copper, aluminium, and nickel.

The photographic plates employed were the Seed "Gilt Edge," and the Cramer "Isochromatic Instantaneous," the former for much the greater part of the work—all except that done in the green, where the latter kind is more sensitive.

The negatives were obtained in the well-known way of exposing a narrow strip along the middle of the plate, with the sides protected, to the arc under pressure; and then with this part protected exposing the sides of the plate to the arc at atmospheric pressure.

The method of measurement and reduction was the same as that described in a former paper,[1] by which each line was twice measured and possible bias in setting practically eliminated. Besides, many of the lines appear on a number of different plates, and they were carefully measured—violet to red and then red to violet—on each plate and the general average taken of all measurements of any given line at each pressure.

The measuring-machine used was furnished by Gaertner & Company, of Chicago. The screw has a millimeter pitch and reads directly to thousandths of a millimeter. The accuracy of the screw was not directly tested, but in identifying lines the wave-lengths computed from measurements agreed very closely with those given in the best tables, and I am confident therefore that such irregularities of the screw as may exist are well within the errors of measure-

[1] *Astrophysical Journal*, **6**, 180, 1897.

ment, except possibly in the case of very narrow or finely reversed lines—such as one never gets under heavy pressure.

The adjustments of a concave grating spectrograph when mounted on tracks at right angles to each other, as used by Rowland and as adopted in the present case, are so well known that ordinarily no description is called for; but in studying displacements or shifts of spectrum lines particular attention must be given to placing the slit rigidly parallel to the rulings on the grating. When this adjustment is not accurately made, a difference in position of the image of the arc on the slit, which often occurs, will produce a displacement of the lines that may be most misleading.

If one has command of sunlight, it is easy properly to set the slit by observing a sharp line and having an assistant operate the slit till the line becomes narrowest and best defined. Arc spectra, too, may similarly be used, though ordinarily not so satisfactorily, owing to the relatively feeble light in the case of very narrow lines. It is also possible to take a series of negatives with the slit in different but known positions, and from these to determine its proper position. Again, by eclipsing the middle part of the slit, taking the light through only its ends, and adjusting it till the two lines thus produced become continuous with each other, an excellent setting may be secured. Finally, if the tracks along which the grating and camera move are horizontal, one can use a silk or other fiber with a weight attached to it — a plumb-line — very close to the end of the ruling on the grating, and adjust the grating until its ruling is quite accurately vertical. The plumb-line can then be placed close to the slit and the latter easily brought also to a vertical position, and therefore parallel to the rulings on the grating.

In my own work, not having access to sunlight, I finally adopted this latter method, but checked it up with all the others.

This particular adjustment is described in detail because in studying changes in wave-length it is vital, so much so that an approximation to parallelism quite sufficient for many purposes may in this case lead to serious errors.

One of the most important effects of pressure on a spectrum line is the shifting of the maximum of its intensity toward the red, an increase of its wave-length, or an increase in the period of vibration

TABLE I

PRESSURE-SHIFT

ALUMINIUM

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3082.27	0.093			3944.16	0.190	0.314	0.372
3092.95	.087			3961.68	.180	.310	.387

BARIUM

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3071.71	0.070			4934.24	0.120		
4554.21	.095	0.162	0.210				

CALCIUM

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3179.45			0.248	4226.91[3]	0.159	0.265	0.398
3933.83[1]	0.065	0.104	.154	4302.68	.085		
3968.63[2]	.080	.136	.203	4318.80	.072		

[1] K, [2] H, [3] *g*.

CHROMIUM

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
2835.75	0.051			4026.30	0.080		
3120.51	.036			4027.24	.076		
3433.72	.074			4039.21	.067		
3436.31	.058			4048.94	.070		
3578.81	.074	0.142		4058.89	.076		
3593.57	.095	.120		4065.84	.120		
3605.46	.083	.150		4067.05	.044		
3615.76	.050			4077.81	.069		
3632.92	.080			4126.67	.040		
3646.26	.045			4171.81	.050		
3666.10	.054			4179.37	.080		
3885.35	.060			4190.32	.058		
3894.20	.072			4191.41	.040		
3908.87	.049			4193.80	.101		
3916.38	.062			4195.09	.083		
3919.31	.052			4198.65	.090		
3921.20	.076			4203.71	.031		
3926.80	.166			4204.61	.087		
3928.79	.050			4208.50	.090		
3941.66	.046			4209.50	.091		
3963.82	.080			4209.90	.048		
3969.89	.063			4221.71	.080		
3976.81	.058		0.160	4240.82	.045		
3984.02	.140			4254.49	.056	0.075	0.130
3990.14	.056			4263.28	.064		
3991.26	.070	.125		4274.91	.076	.123	
3992.95	.066			4280.53	.061		
4001.58	.084			4289.87	.087	.130	.218
4012.63	.080			4295.92	.056		
4022.38	.066			4297.91	.061		
4023.90	.065			4301.33	.052		
4025.14	.061			4323.70	.050		

TABLE I—*Continued*

CHROMIUM—*Continued*

λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.
4344.66	0.057	0.085	0.128	4646.33	0.065	0.100	
4351.91	.065	.075		4651.44	.095		
4359.78	.066	.110		4652.31	.058	.088	
4363.25	.064			4680.65	.056		
4371.44	.060	.084		4729.89	.129		
4497.02	.040	.069		4730.88	.101		
4526.65	.080			4756.30	.146		
4535.95	.075			4792.61	.183		
4546.15	.060			5204.67	.164		
4580.22	.040			5206.20	.156		
4600.92	.085			5208.58	.092		
4613.54	.050			5247.68	.132		
4616.28	.053	.089		5348.50	.196		
4626.31	.056						

COBALT

λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.
3894.21		0.143		4092.55	0.042		
3995.45	0.072	.131	0.150	4118.92		0.094	
3998.04	.054			4121.47	.070	.104	

COPPER

λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.
2883.03		0.040		3274.06	0.090	0.230	
2961.25		.052		4242.42		.473	
2997.46		.046		4249.21		.273	
3010.92		.044		4259.63		.387	
3063.50		.041		4378.40		.420	
3073.89		.026		4415.79		.409	
3094.07		.032		4539.98		.459	
3194.17		.047		4587.19		.513	
3247.65	0.090	.145		4704.77		.460	

IRON

λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 60 Atmos. Å. U.	At 101 Atmos. Å. U.
2931.55	0.026			3307.33	0.030		
2991.78		0.062		3314.86	.120		
3037.54	.052			3323.84	.073		
3047.71	.053			3329.00	.052		
3050.90		.049		3355.27	.064		
3059.19	.063			3366.88	.035		
3067.30		.071		3369.62	.048	0.110	
3175.53	.068			3370.87	.050		
3229.19	.013			3380.17	.054		
3233.14	.038			3384.05	.030	0.50	
3254.47	.060			3392.37	.036		
3265.73	.091			3392.74	.069	.120	
3271.12	.100	.123		3394.65	.040	.070	
3291.10	.168			3399.39	.045	.074	
3298.25	.050			3401.60	.080		
3306.50	.072			3402.33	.060		

TABLE I—*Continued*

IRON—*Continued*

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3404.41	0.055	0.076		3647.99	0.090	0.135	
3407.55	.060	.108		3649.65	.060		
3411.43	.035			3650.42	.025		
3413.22	.056	.088		3651.61	.065	.105	
3414.83	.060	.068		3659.65	.050	.080	
3415.61	.060			3669.65	.050	.060	
3417.92	.058	.097		3670.20	.047		
3418.58	.060	.100		3676.44	.050	.086	
3422.69	.056			3677.76	.052		
3424.36	.052	.090		3680.03	.062	.067	
3425.08	.080			3683.18	.040		
3427.21	.053	.104		3684.24	.053		
3428.26	.060			3687.58	.090	.120	
3440.69	.050			3689.58	.084		
3441.07	.050			3695.18	.070		
3443.96	.045	.066		3703.68	.086		
3445.22	.054			3704.59	.046		
3447.37	.050			3705.70	.054	.070	
3450.41	.057			3709.37	.095	.140	
3451.99	.059			3716.04	.107		
3458.39	.111			3720.07	.047	.070	0.091
3465.95	.050	.067		3722.69	.050	.084	
3471.40	.040			3724.51	.054		
3475.52	.048	.066		3727.78	.100	.138	
3476.75	.036	.059		3733.46	.050	.080	
3485.42	.065			3735.00	.092	.150	.180
3490.65	.052	.080		3737.27	.040	.065	.093
3495.37	.048			3738.44	.078		
3497.20	.050			3743.58		.155	
3497.92	.045	.075		3745.67	.050	.086	
3506.59	.047			3745.95	.050		
3508.58	.095			3748.39	.040	.063	.090
3513.91	.063	.100		3749.61	.085	.160	.180
3521.36	.085			3752.57	.098		
3558.62	.085	.150		3758.36	.090	.140	.184
3565.50	.074	.128		3763.90	.095	.180	.195
3570.23	.075	.141		3765.66	.106		.160
3581.32	.083	.133		3767.31	.118	.160	
3585.43	.100	.162		3788.01	.090	.180	
3585.84	.076			3795.13	.093	.135	
3587.10	.072	.127		3798.65	.085	.170	
3603.34	.062			3799.68	.075	.140	
3605.62	.030			3805.47	.092		
3606.83	.059			3813.12	.058	.101	
3608.99	.072	.117		3815.97	.110	.175	.180
3618.92	.080	.120		3820.56	.125	.172	.200
3621.61	.068			3824.58	.040	.050	.070
3622.15	.060			3826.04	.090	.140	.200
3623.33	.040			3827.96	.102	.150	
3631.62	.090	.143		3834.37	.110	.165	.210
3638.44	.061			3840.58	.098	.165	.237
3640.53	.065			3841.19	.100	.180	

TABLE I—*Continued*

IRON—*Continued*

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3850.11	0.082	0.173	0.235	4236.09	0.274	0.435	
3856.49	.038	.057	.070	4245.39	.060		
3860.03	.042	.071	.105	4250.93	.089	.138	0.180
3865.65	.103	.180		4260.64	.246	.399	.540
3868.03			.082	4271.93	.083	.132	.185
3872.61	.108	.151		4282.58	.043	.061	.093
3878.82		.066		4294.26	.084	.130	
3880.38	.056	.083	.101	4307.96	.090	.140	.214
3887.17	.073	.130		4315.21	.036	.051	.097
3888.63	.089	.174		4325.92	.097	.143	.189
3893.47	.072			4337.14	.090	.152	
3895.75	.030	.047		4352.86	.052	.074	
3899.80	.036	.067	.070	4367.68	.060	.100	
3903.06	.095	.151	.170	4369.89	.055	.090	
3904.00	.056			4376.04	.039	.060	
3906.58	.050			4379.36	.101.		
3920.36	.033	.060	.077	4383.70	.125	.153	.180
3923.00	.032	.060	.070	4384.82	.130		
3928.05	.038	.064	.080	4404.88	.110	.150	.207
3930.37	.047	.065	.090	4407.80	.180		
3948.87	.050		.115	4408.54	.160		
3950.05	.066		.130	4415.27	.087	.146	.220
3956.77	.036			4422.67	.065	.105	
3969.34	.089	.148		4427.44	.055	.086	
3977.83	.042	.077	.105	4430.74	.190		
3981.87			.150	4442.46	.190		
3984.08	.085			4443.30	.060		
3986.27	.061			4447.85	.180		
3997.49	.048	.076	.087	4454.50	.080		
3998.16	.066			4459.24	.160	.203	.250
4005.33	.103	.152	.215	4461.75	.060		
4009.80	.040	.075		4466.70	.056	.074	
4014.63	.050	.082		4476.20	.072	.120	
4017.23	.062			4482.35	.125		
4021.96	.037	.073	.108	4494.67	.200	.290	
4045.90	.103	.170	.200	4528.78	.172	.250	
4063.63	.107	.168	.201	4531.25	.075		
4071.79	.092	.178	.260	4547.95	.097	.180	
4107.58	.060	.109	.145	4592.75	.110		
4109.88	.062	.092	.115	4603.03	.093	.150	
4118.62	.085	.110	.190	4647.54	.070		
4132.15	.105	.212		4662.09	.067		
4134.77			.138	4691.52	.070		
4143.96	.116	.198		4710.37	.060		
4156.88		.096	.148	4736.91	.085		
4172.81	.140			4762.48	.160		
4181.85			.170	4786.91	.076		
4184.99	.040	.060	.085	4789.74	.080		
4199.19	.073	.120	.190	4859.86	.390		
4202.15	.071	.130	.173	4871.43	.420		
4219.47	.074	.111	.145	4878.33	.400		
4233.76	.240			4919.11	.375		

TABLE I—*Continued*

IRON—*Continued*

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
5171.71	0.075			5429.74	0.085		
5195.03	.080			5434.66	.120		
5269.65	.083			5447.05	.095		
5328.15	.100			5455.80	.105		
5371.62	.095			5497.52	.110		
5397.27	.080			5501.61	.095		
5400.60	.063			5506.92	.120		
5405.91	.100			5615.81	.080		
LANTHANUM							
3916.16	0.030			4086.86	0.144		
3929.34	.092			4238.55	.098		
3988.69	.076			4269.64	.085		
3995.90	.118			4280.43	.058		
4031.85	.088			4430.09	.051		
4037.26	.064			4570.20	.066		
4043.04	.170						
LEAD							
3639.71			0.306				
MAGNESIUM							
2852.22		0.160	0.190	5183.84	0.275		
MANGANESE							
3200.06	0.070			4063.38	0.106		
4018.25	.070	0.120		4083.75	.080		
4030.87	.052	.090	0.150	4266.08		0.084	
4033.18	.050	.091	.112	4451.75	.180		
4034.60	.050	.091		4762.54	.145		
4035.88	.086			4766.58	.158		
4041.49	.068	.103		4783.60	.290		
NICKEL							
3002.60			0.107	3369.66	0.077		
3003.73			.103	3372.12	.048		
3012.10			.105	3374.35	.029		
3038.05			.097	3380.70	.096		
3050.88	0.032	0.077	.101	3391.21	.070		
3054.40	.041		.102	3393.10	.063		
3057.72	.050	.090	.127	3414.90	.077		
3101.61	.048			3423.80	.084		
3102.00	.059			3433.71	.094		
3134.26	.060		.122	3437.45	.063		
3233.11	.049		.115	3446.34	.071		

TABLE I—*Continued*

NICKEL—*Continued*

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3452.98	0.062			3664.24		0.110	
3458.51	.091			3670.57		.088	
3461.78	.067			3674.28		.070	
3467.63	.063			3688.58		.068	
3469.64	.095			3722.63		.111	
3472.68	.080			3736.94		.083	
3493.10	.081			3775.71		.088	
3501.00	.050			3783.67		.058	
3510.47	.083			3807.30		.076	
3519.90	.075			3858.40		.117	
3524.65	.096			3972.31		.075	
3548.34	.080			3973.70		.140	0.176
3561.91	.063			4331.78	0.088	.150	.204
3566.51	.091			4401.70			.480
3571.99	.100			4459.21			.625
3588.08	.092			4470.61		.580	
3597.84	.102			4520.20		.120	
3602.41	.082			4592.69	.320	.620	
3609.44	.072			4600.51	.464		
3610.60	.101			4605.15	.280	.600	
3612.86	.080			4648.82	.270	.660	
3619.52	.065			4686.39	.325	.557	
3624.87	.060			4714.59	.274		
3662.10	.053			4756.70	.297		

PALLADIUM

3002.74	0.052			3460.93	0.087		
3028.05	.056			3481.31	.096		
3065.41	.082			3517.08	.058		
3114.19	.066			3634.85	.063		
3142.97	.040			3690.49	.070		
3219.08	.050			3894.33	.098		
3251.89	.085			3958.79	.119		
3259.01	.094			4213.11	.130		
3287.38	.094			4388.80	.290		

POTASSIUM

4044.29	0.504			4047.36	0.480		

SILICON

2881.70	0.080			3905.70	0.184		

STRONTIUM

4077.88	0.070			4607.52	0.170	0.268	
4215.66	.100						

TABLE I—*Continued*

TITANIUM

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3186.58	0.121			3989.92	0.049	0.097	0.140
3200.08	.057			3998.77	.047	.078	.130
3234.68	.042			4009.06	.055	.081	
3236.72	.033			4021.98	.038	.064	
3242.15	.035			4286.15	.103		
3253.04	.044			4287.55	.087		
3349.56	.027	0.046		4291.07	.115		
3354.80	.035	.054		4295.91	.100		
3361.41	.037	.077		4300.73	.104		
3370.61	.045			4301.23	.110		
3371.62	.030	.050		4306.07	.104	.150	
3372.91	.034	.067		4318.83	.042		
3373.03	.025			4427.28		.037	
3386.10	.051	.092		4533.42	.176	.270	
3387.97	.030			4534.97	.124	.195	
3461.69	.080			4544.83	.080		
3635.61	.058			4682.08	.077		
3642.82	.053			4691.50	.080		
3653.61	.050			4758.30	.067		
3685.30	.012			4759.44	.092		
3904.95	.073			4841.00	.029		
3921.56	.068			4981.92	.077	.152	
3948.80	.045			4991.24	.135	.212	
3956.45	.030			4999.67	.120	.165	
3958.33	.045			5007.42		.225	
3981.91	.056	.097	150	5013.45	.056	.100	

TUNGSTEN

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3300.97	0.040			4083.13	0.096		
3311.53	.038			4102.85	.036	0.050	0.082
3326.33	.027			4241.62	.086		
3331.84	.047			4244.52	.060		
3361.26	.071			4269.53	.064		
3373.89	.046			4484.37	.030		
3429.72	.077			4610.12	.087		
4008.91		0.080		4660.00	.071		
4015.39	.060			5053.50	.044		
4019.37	.070	.128					

ZINC

λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.	λ	At 42 Atmos. Å. U.	At 69 Atmos. Å. U.	At 101 Atmos. Å. U.
3075.99		0.056		3740.12		0.250	0.320
3683.63		.220	0.350	4058.02	0.200	.280	.382

of the luminous particle. Table I shows the measured amount of this increase of wave-length in thousandths of an Ångström unit for each line measured, and for each pressure under which it was taken.

The wave-lengths used for aluminium, barium, calcium, copper, iron, lead, magnesium, potassium, strontium, and zinc are taken from tables given by Kayser and Runge; those for chromium, cobalt, manganese, nickel (in part), and titanium (in part), from Hasselberg's tables; and those for lanthanum, nickel (in part), palladium, silicon, titanium (in part), and tungsten, from tables by Exner and Haschek.

It seems convenient to list some of the more conspicuous effects of pressure on arc spectra, and, whenever necessary, to comment on each separately.

1. The brilliance of the arc becomes much greater as the pressure, if due to atmospheric air, with which all my work was done, is raised. What the effect of wholly inert gases would be, I cannot say. Presumably this is caused by the more rapid wasting-away of the electrodes; possibly because of the increased resistance and shortened arc—a greater concentration of energy and it may be a corresponding increase in temperature—though the effect of pressure on the temperature of the electric arc seems to be an open question.

2. Reversals are decidedly more pronounced and frequent under heavy than under light pressures, and especially so in the ultra-violet region. This probably is due to a denser layer of absorbing vapors surrounding the arc, and, like 1, may, in part at least, be accounted for by the more rapid burning of the electrodes.

3. Pressure seems to increase the width of all lines, though quite unequally, and to make them somewhat nebulous, especially at the edges. Occasionally lines are found on certain plates, that appear to be narrowed by heavy pressure; but probably this is due to a decrease in exposure, since under these conditions they are rather weak, and therefore only show at their places of maximum intensity.

4. The lines of the carbon (cyanogen) bands are not appreciably displaced, if at all, even at the highest pressures used; though, like the individual lines of the elements, they are increased in width.

5. The wave-lengths of all other lines examined increase approximately proportional to the increase in pressure up to the highest used, though this increase or shift is very different, not only for different elements, but even for different lines of the same element.

6. The amount of shift of a given line is practically independent

of whether or not it is reversed; that is, the emission and the absorption are similarly and equally affected.

7. In general the pressure-shift of the spectrum lines seems to increase with the wave-length, but probably this is true only of lines of the same series; at any rate, it is not conspicuous in the case of iron, nickel, and other elements whose lines appear to belong to many series, or to none.

8. So far as I can judge from the scanty numerical data on the Zeeman effect, in general those lines which are strongly separated by a magnetic field are correspondingly largely displaced by pressure; and conversely those, like the lines of bands, that have but little if any Zeeman separation, are but slightly if at all shifted by pressure.

9. The relative intensities of lines at high and low pressures vary exceedingly. In general, the intensity of titanium lines increases with increase of pressure, while iron in this particular behaves most irregularly; some of its lines become more intense as the pressure is increased, while others are diminished, a number entirely disappearing even at 40 atmospheres. Among those that disappear at this pressure are λ 4222.32, 4250.28, 4299.42, 4878.33, 5049.94, and 5191.56.

As already explained, the electrodes burn away more rapidly as the pressure is raised, and therefore the increased intensity of the lines might be expected from the greater rate of supply to the arc of the material to which they are due, and possibly, too, in part to the increased potential gradient. But the opposite effect, the enfeebling of many lines, calls for some other explanation. It may be that their emission, too, is increased, but more or less neutralized by a large absorption factor. Just why this should be so, if indeed it is the correct explanation, is not clear; but neither is it obvious why lines in the open arc, for instance, differ so greatly in the phenomena of reversal, that is, in their relative amounts of emission and absorption.

Since sun-spot lines give similar effects,[1] some of them being intensified, while others are enfeebled, I sought to determine whether there was any connection between sun-spot and pressure phenomena. Unfortunately, however, enfeebled sun-spot iron lines are so faint

[1] Hale and Adams, *Astrophysical Journal*, 23, 11, 1906; Adams, *ibid.*, 24, 69, 1906.

in the arc that they do not show appreciably on my plates. However, λ 5191.56, which vanishes under heavy pressure, is somewhat intensified in sun-spots. So far, then, as the evidence of a single line is worth anything, it would appear that the light in sun-spots does not come from any great depth in the sun's atmosphere—that the spots, whatever their cause, are distinctly surface phenomena. A careful examination of properly selected lines for pressure-shift in spots should be of value in this connection.

10. The shift of spectrum lines seems to be chiefly a function of total and not of partial pressure; that is, the displacement of a line does not greatly, if at all, depend upon the amount of material in the arc to which the line in question is due. Kayser, among others, has shown this to be true at atmospheric pressure, and, if true at one pressure, there is no very clear reason why it should not be equally true at others.

It has been claimed,[1] that the shift is a function of partial pressure, but my plates do not justify this conclusion. While it is true that the measurements of different plates do not always closely agree, nevertheless these differences are generally referable to some instrumental disturbance, all lines on the plate being similarly affected, or else apply to lines whose errors of measurement are very large. At any rate, they are such that I do not feel justified in referring them to anything other than mere accident.

11. The increase in wave-length of the spectrum lines is only a small part of that which would be expected if the luminous particles behaved like Hertzian oscillators.

The period of such an oscillator is known to be expressed by the equation

$$T=2\pi\sqrt{LC}\ ,$$

in which T is the period, L the inductance, and C the capacity. With other things equal, C increases directly with the inductive capacity of the dielectric in which the oscillator is placed.

It is also known that in the case of gases $\mu_\lambda - 1 = ad$, where μ_λ is the refractive index for wave-length λ at the density d, and a is a constant; but for all ordinary pressures $\mu_\lambda - 1$ is small, and therefore so too is a.

[1] Huff, *Astrophysical Journal*, 14, 41, 1901.

But since $\mu^2 = K$, the specific inductive capacity, we have $K = (ad+1)^2$ or $d(a^2d+2a)+1$. Therefore $K-1=2ad$ very nearly; that is, K is approximately a linear function of the density. Now, since K for air at ordinary density is about 1.0006, and for air at a pressure of 100 atmospheres roughly 1.06; then, neglecting temperature effects, we might expect, on the assumption that spectrum lines are due to Hertzian oscillators, that the period at one atmosphere will be to that at one hundred atmospheres as $\sqrt{1.0006}$ is to $\sqrt{1.06}$; or, in symbols, that

$$\frac{\lambda_1}{\lambda_{100}} = \frac{\sqrt{1.0006}}{\sqrt{1.06}};$$

and therefore "g," of wave-length 4227 at 1 atmosphere, would become λ 4350.6 at 100, or be shifted 123.6 Ångström units. But its measured shift for the same conditions is only 0.4 of an Ångström unit, or one three-hundredth of the calculated amount. Besides, lines of the same wave-length should have equal shifts, which is not in accord with experiment. From these facts it seems unlikely that the increase in the specific inductive capacity of the region in which a substance is placed can be the cause of the pressure-shift of its spectrum lines; nor is it at all clear just how it could be, since the interior of any given atom probably is not altered by changes in the density of the surrounding gas.

This same line of argument has been offered by W. B. Anderson,[1] but I venture to discuss it rather fully because the statement in a former paper[2] that it would not be easy to decide the question experimentally has led to some misunderstanding.

The effects of different gases might be tried on arc spectra, as has been done in an excellent piece of work on spark spectra,[3] but this is already in great measure secured by using metal poles, and carbon poles with metallic impurities; and the difference in the shifts, as already explained, is not decisive. Besides, the difference in the inductive capacities of the gases is a less percentage of the total of either than the error of measurement is of the total shift;

[1] *Astrophysical Journal*, **24**, 253, 1906.

[2] Humphreys, *ibid*, **24**, 253, 1906.

[3] W. B. Anderson, *ibid.*, **24**, 221, 1906.

and therefore, even if the shift is a linear function of the inductive capacity, it would not be easy to prove it by experiment.

Anderson states that in the case of spark spectra pressure-shifts are greater in carbon dioxide than in hydrogen, and gives a table[1] of such lines. This table, all that he gives on this subject, does not appear definitely to prove the above statement. Only four lines admit of comparison, and of these, when reduced to the same pressure, two have greater measured shifts in hydrogen and the other two greater in carbon dioxide.

There is evidence of a typographical error in the data for one of the lines in hydrogen, but, leaving this line out, there is still one line with greater measured shift in hydrogen to two greater in carbon dioxide. Besides, the difference in measurements, when reduced to the same pressure, of a line in carbon dioxide is of the same order of magnitude as the difference between measurements on the same line in carbon dioxide and hydrogen. Finally, from the widths of the reversals, these lines could not be measured with much accuracy.

Therefore, in spite of this excellent paper, the influence of specific inductive capacity on pressure-shift does not appear to be well established.

In this connection it is interesting to compare arc- and spark-shifts,[2] under definite, though unavoidably different, conditions.

Table II gives this comparison for a number of iron lines. The first column gives the wave-length; the second, the average of several measurements of shift of spark lines (the inductance being 75 millihenrys and the capacity 0.0270 microfarads), produced in carbon dioxide at 50 atmospheres pressure; the third, the average corresponding shifts, computed for the same pressure from all measurements, of the arc lines produced in air by a direct current of about 15 amperes.

For another plate Anderson gives decidedly greater measured shifts, but in this case the reversals were much wider, and therefore, if I may judge from similar plates of my own, very deceptive, giving larger measured shifts than do the same lines produced under the same conditions, but with longer exposures, and therefore narrower reversals. It will be noticed that the general agreement is

[1] *Loc. cit.*, 24, 252, 1906.

[2] Anderson, *loc. cit.*, p. 250.

TABLE II

SHIFTS, IN ÅNGSTRÖM UNITS, AT FIFTY ATMOSPHERES PRESSURE OF SPARK IRON LINES IN CARBON DIOXIDE AND OF THE SAME ARC LINES IN AIR

λ	Δλ Spark Anderson	Δλ Arc Humphreys	λ	Δλ Spark Anderson	Δλ Arc Humphreys
3687.58	0.107	0.096	3865.65	0.075	0.124
3709.37	.119	.106	3969.34	.092	.105
3758.36	.089	.099	3977.83	.075	.053
3763.90	.082	.112	3997.49	.079	.052
3765.66	.097	.102	4021.96	.093	.050
3767.31	.115	.110	4045.90	.106	.114
3805.47	.068	.107	4063.63	.105	.115
3813.12	.074	.070	4071.79	.131	.122
3815.97	.104	.114	4132.15	.107	.136
3824.58	.052	.040	4156.88	.073	.072
3827.96	.126	.113	4199.19	.090	.089
3834.37	.095	.117	4219.47	.097	.080
3856.49	.055	.040			

fairly close, showing that presumably neither the nature of the surrounding gas nor the mode of rendering the atoms luminous changes very greatly the magnitude of the shift. However, in the *Publications of the Yerkes Observatory*, Volume III, Part II, Plate XXII, Hale and Kent give a comparison between displacements they obtained with high-potential discharge in gases and those I obtained with the arc under similar conditions. Five of the lines agree reasonably well, three show much greater displacements when produced by sparks, while one, λ 3606.85, was not formerly measured by myself and is therefore left uncompared.

The present paper leaves these relations exactly as they were, except that λ 3606.85 has now been measured in the arc under pressure, and gives a disagreement even greater than does any one of the other compared lines, so that the possible difference of pressure-shift of arc and spark lines is still an open question.

In regard to the atom and its mode of vibration, the solution of which is one of the great aims of spectroscopic work, it seems that the Zeeman phenomenon demands that, whatever its substance, it shall, in part at least, be electrical; that the spectrum lines are not caused by simple mechanical vibrations of uncharged bodies such as are produced by an elastic solid; while the pressure-shift shows that

specific inductive capacity has but little, if any, influence on the period of whatever it is to which these lines are due.

As pointed out in a former paper,[1] since the spectrum lines of a radiant atom of whatever element are affected by a magnetic field, it seems certain that the atom itself must possess a magnetic field of its own, and therefore affect, in the Zeeman sense, the lines produced by its neighboring atoms, whether of the same or of different elements, and in turn suffer similar effects from them. It can be shown that the "Saturnian," and therefore magnetic, atom will, when placed in an external magnetic field, produce, as a result of induction, the Zeeman phenomenon; and also that a number of such atoms, when close together, will, through their mutual inductions, produce the phenomenon of pressure-shift, besides materially adding to the width of their spectrum lines.

The experimental discovery of either of these two phenomena, the Zeeman and the pressure-shift, might, in my opinion (since I believe them to be essentially the same thing), have led to the prediction of the other. As a matter of fact, the more obscure one, the pressure-shift, was first discovered, but its explanation in terms of interacting "Saturnian" or magnetic atoms did not suggest itself till a number of years after the independent discovery of the Zeeman effect.

Since the displacements due to different pressures of spectrum lines can be measured, it is therefore possible to use these displacements in turn as measures of pressures even at places where no other method is available, and it may therefore serve to give some idea, among other things, of the depths in the sun at which different spectroscopic phenomena have their origin.

I am painfully aware that this paper does not include as many elements as it should, nor is it as exhaustive of any one as it profitably might be; but it is hoped that together with former papers enough is given to indicate what further work should be undertaken. I trust, too, that others may join in this investigation, since an exhaustive study of the subject will require much labor.

Much remains to be done, both on pressure-shift and on the Zeeman phenomenon, before the one-to-one relation between them

[1] Humphreys, *Astrophysical Journal*, **22** 233. 1905.

can be definitely established or disproved. Besides, it is not improbable that a fuller study of pressure phenomena may lead to the discovery of groups and series of lines, either through their relative shifts, the pressures at which they cease to exist as lines, or other pressure effects. It may be possible to study the pressure effects on individual parts of a complex line as shown by the echelon or other powerful analyzer, and undoubtedly such an investigation would be of decided interest.

These, while not all, are among the more obvious pressure investigations I hope to see taken up and pushed to some definite conclusion.

The accompanying plate may be of some interest. In all cases the middle strip was taken at the high pressure and the sides at 1 atmosphere.

I shows in the third order and at 42 atmospheres, H and K, and between them two aluminium lines.

II. Second order, 69 atmospheres, gives *g*, shows the greatly displaced iron line $\lambda 4260.64$, and two iron lines, $\lambda 4250.31$ and $\lambda 4299.38$, that vanish under pressure.

III. Third order, 101 atmospheres, otherwise same as II.

IV. Second order, 101 atmospheres, ultra-violet iron lines.

This shows that many lines are still fairly good at this high pressure.

All the spectrum negatives used in this work were obtained in the physical laboratory of the University of Virginia, and I wish here to thank President Alderman and Professor Smith for their kindness in placing its excellent equipment at my disposal.

MOUNT WEATHER OBSERVATORY
BLUEMONT, VA.
May, 1907

APPARATUS FOR OBTAINING ELECTRIC ARCS UNDER HEAVY PRESSURE

By W. J. HUMPHREYS

A difference of potential of 110 volts is sufficient to maintain a fairly constant arc between carbon poles, either pure or mixed with metallic salts, provided the surrounding pressure is not greater than 10 to 12 atmospheres. With a difference of 220 volts the difficulty of maintaining a steady arc between fixed poles does not become excessive until a pressure of something like 25 atmospheres is reached. Higher voltages of course will produce good arcs with still greater pressures, but insulation becomes somewhat more troublesome; besides, when the apparatus must be worked with in the dark and one has to take chances on getting an occasional shock, high voltages are by no means desirable. Finally, the above being the usual commercial voltages, higher ones often are not easily obtained.

By making one of the poles in the form of a disk and rotating it while the other, in the shape of a rod or bar is brought up so as to touch it some distance from the center, an arc may be maintained with 220 volts between carbons, or carbon and metal, at much higher pressures. I have repeatedly used such an arc in spectroscopic work at 101 atmospheres, and found it still moderately constant and satisfactory.

The apparatus that proved efficient for this purpose is shown in section in Fig. 1, and mounted as in actual use in Fig. 2.

Referring to Fig. 1, the large vessel, *1*, is a forged cylindrical steel shell 6 inches (15 cm) in diameter and 16 inches (40 cm) long, both inside dimensions, with walls $1\frac{1}{2}$ inches ($3\frac{3}{4}$ cm) thick. A heavy walled block, *2*, is screwed into the side of this cylinder and made air-tight. A thick piece of quartz, *4*, is held tightly against the end of the tube, *2*, by means of the cap, *3*. Quartz is used to let ultra-violet radiation through, and besides it has the advantage of being very strong. A thin rubber or leather ring is placed between the quartz block and the end of the tube, *2;* and by means of a spanner-wrench, the cap, *3*, can safely be screwed up till the leak past the pack-

ing ring is negligible. It is necessary to cement the quartz block into its seat in the cap, *3*, to prevent any trace of leak passing by its outer face. If this is not done and a slight leak occurs — which is reasonably certain to happen — the outer face of the quartz will quickly be covered by moisture, and the beam of light seriously interfered with. That variety of cement known as "Khotinsky, hard" was used. It is easily applied and entirely satisfactory. The ends of the cylinder are drawn out to a proper size, bored in line with each other, and threaded on the outside. Partitioned metal pieces, *5*, are fitted to each of these ends, and screwed down with a spanner-wrench till their partitions come in contact with the glands, *9*, as shown, and force them against the packings, *10*, as tight as is necessary to prevent objectionable leakage about the steel tubes, *14*, that carry the electrodes.

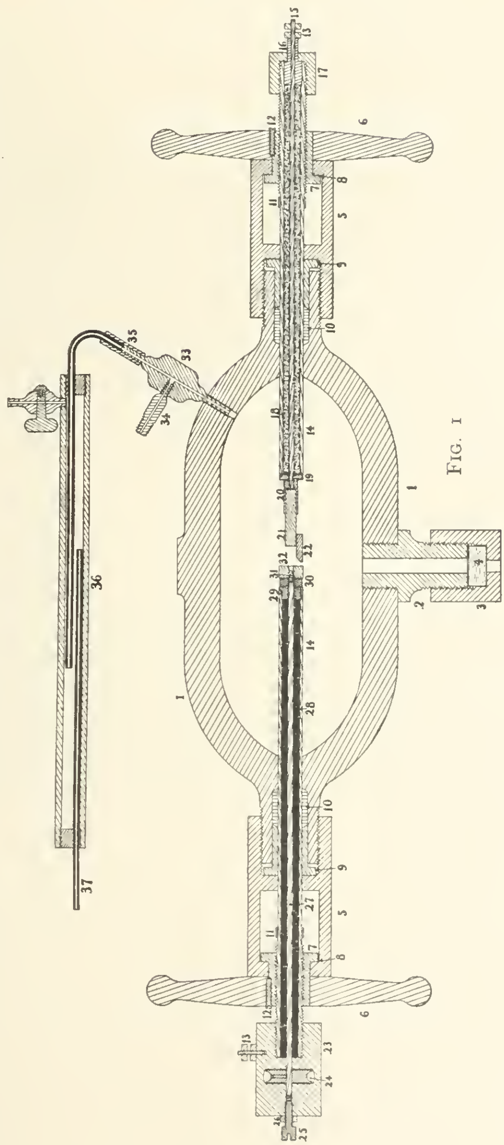

FIG. 1

In assembling the apparatus (in this particular both ends are alike) and before the tube, *14*, is introduced, the nut, *7*, is placed in the outer chamber of *5*, through an opening for that purpose, and slipped forward till shouldered against it at *8*. The hand-wheel, *6*,

is then fitted on this nut and made fast to it by means of the binding screw, *12*. The nut, *7*, is large enough to let the smooth part of *14* pass through it, and therefore when the pressure on the packing, *10*, is relieved by slightly unscrewing *5*, the electrodes may easily be removed from the cylinder; this operation is frequently necessary and therefore should be made as easy as possible. When in place, as shown, the electrodes are easily adjusted endwise by turning the hand-wheel, *6*, and therefore the nut, *7*.

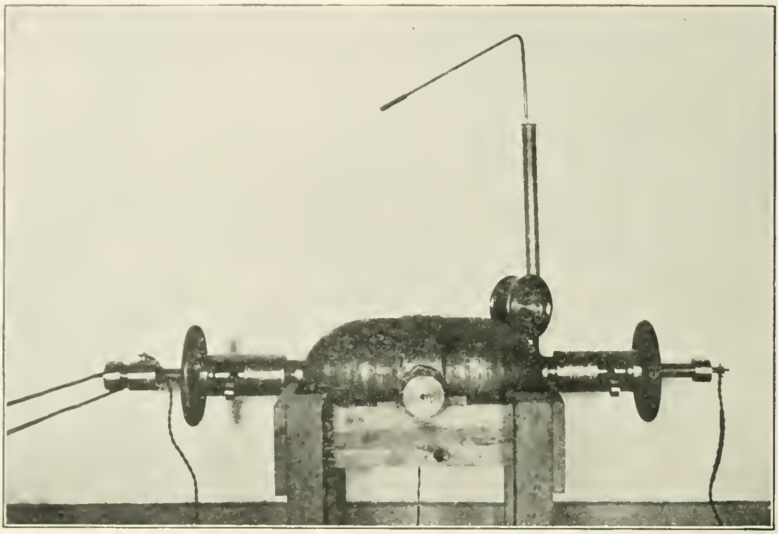

FIG. 2

A metal rod, *15*, provided with a binding post, *13*, is screwed through an ebonite block, *16*, which in turn is screwed into the tube, *14*, and further secured in place by the cap, *17*. The inner end of this rod passes through a mica block, *19*, against which the thimble, *20*, is tightly screwed. This thimble carries the fixed pole, which may be a carbon, or a metallic rod, beveled so as to touch eccentrically the rotating electrode, *32;* or it may carry a metal rod, *21*, to which the electrode, *22*, is made fast by any convenient method. Merely tying them together with copper wire is generally sufficient.

The space between the rod, *15*, and the wall of the tube, *14*, is filled with powdered or ground mica, *18*, which both insulates

electrically, and prevents absolutely any air leakage through the tube.

To prevent possible damage to the block of mica, *19*, from inequalities of pressure on opposite sides of it, a few small holes were bored very near it through the tube, *14*.

The rotating pole, *32*, is carried on the end of a small shaft, *27*, which is turned by means of a light round belt running from the pulley, *24*, to a suitable motor. This shaft passes through a close bearing in the cap, *23*, and the end-thrust is taken by a steel ball between the cupped ends of the shaft and the screw, *25*. The inner end of the shaft passes through a loose bearing in the metal block, *29*, and is screwed into the thick metal disk, *30*. A short rod, *31*, is also screwed into the disk, *30*, and to its other end is screwed the rotating pole, usually of carbon. The direction of rotation is such that friction against the pole, *22*, will tighten the pole, *32*. The short rod, *31*, is desirable because it is much more easily replaced than the shaft would be, and occasionally it gets badly injured as the rotating disk is burned away. The shaft is adjusted endwise by means of the screw, *25*, and when properly placed is made secure with the lock-nut, *26*.

The space between the rotating shaft and the wall of the tube, *14*, that carries it is filled with Ceylon graphite which is micaceous in its structure, and serves to help conduct the current taken in at the binding post, *13*, on *23*, to the shaft, *27*. Besides, it prevents almost absolutely any air-leakage through the tube, since any opening tends at once to be filled by graphite which is blown into it; and finally, no matter how tightly packed, the graphite is still a lubricant. Even when the pressure was 101 atmospheres the shaft was rotated with the greatest ease.

A fixed arc may be had, when the pressure is not too high, either by not turning the disk, or by making both poles of the fixed type, in which case there is no occasion to use poles placed eccentrically like *22*.

The gas from the compressor enters by means of the tube, *37*, into the liquid separator, *36*, and thence as shown into the shell containing the arc. The place of admission must be so situated and directed that no moisture shall be blown on to the quartz block, *4*, and

the draft shall not strike the arc itself. The first condition is always necessary, and the second desirable in the case of long exposures, since the pump must then be kept running with its blow-off valve set, in order to maintain a constant pressure shown by a gage attached to *34*. The pressure is let off by opening the stop-cock on the separator, *36*, which at the same time gets rid of any accumulated liquid.

In use the length of the shell is placed at right angles to the length of the slit of the spectroscope; and the separator, *36*, of course stands vertical.

It might seem that there would be trouble in seeing the poles, and therefore in properly adjusting them; but this is easily done by means of an incandescent electric light and an ophthalmoscope mirror. In making such adjustments it is most convenient to have the cap, *3*, removed.

It is desirable, when making the endwise adjustments of the poles, that the fixed one at least shall not rotate as a result of turning the nut, *7*. This trouble, though in practice it seldom happened, can be prevented by a clamp shown at *11*, the outer end of which presses against the edge of the opening in *5*.

The apparatus may seem not entirely simple, but there were many conditions to be met, and as constructed it gave such satisfactory results that the labor of making it was amply justified. The only part difficult to obtain was the forged-steel shell; this was finally furnished in an excellent condition by the Janney Steinmetz Co., of Philadelphia.

The apparatus in its completed form was paid for in part by a grant made by the Rumford Committee of the American Academy of Arts and Sciences, to whom I wish to express my sincere appreciation.

MOUNT WEATHER OBSERVATORY
BLUEMONT, VA.
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MODIFICATION IN THE APPEARANCE AND POSITION OF AN ABSORPTION BAND RESULTING FROM THE PRESENCE OF A FOREIGN GAS

By R. W. WOOD

In the course of a somewhat extended study of the fluorescence and other optical properties of mercury, I have found what appears to be indisputable evidence that the appearance, and even the apparent position, of an absorption band can be profoundly modified by the presence in the absorbing vapor of a chemically inert gas. Reciprocal actions between dissimilar molecules have been sought for a long time, and a number of phenomena have been observed which have been claimed to show that an emission spectrum can be modified by the presence of foreign molecules; but objections can be raised in practically every case thus far recorded.

Professor Kayser, in his *Spectroscopy*, Vol. 2, p. 250, says:

> Ich glaube nicht, dass ein einziger dieser Versuche zu dem Schlusse zwingt, dass die Schwingungen eines Moleculs geändert werden durch Zusammenstösse mit fremden Moleculen, sondern dass es sich in allen diesen Fällen um chemische Wirkungen, um geänderte Art oder Vertheilung der elektrischen Entladung oder um veränderte Temperatur handelt.

I have submitted the photographs, which illustrate this paper, to Professor Kayser, and he has written me that he regards them as the first conclusive evidence that the collision of a molecule with a dissimilar one may affect its vibrations in a manner different from that resulting from collision with a similar molecule.

The vapor of mercury shows strong selective absorption in the ultra-violet. There is a very heavy band at λ 2536, in the neighborhood of which powerful anomalous dispersion occurs, and a weaker, less sharply defined band at λ 2350, which does not appear to influence the dispersion to any great degree. It is with the first of these two bands that we are chiefly concerned. With small vapor-densities we have in fact two very narrow lines, a strong one at λ 2536 and a weaker one at λ 2539, the two reminding one strongly of the D lines.

If a drop of mercury is placed in a small quartz bulb, which is

thoroughly exhausted and sealed, the appearance of the absorption spectrum for different vapor-densities is shown in Fig. 1, Plate V. A condenser discharge between cadmium electrodes was used as a source of light, as the continuous background is of considerable intensity, and the bright lines form useful reference points.

The bulb was placed in an air-bath, the temperature of which was gradually raised, and the spectra were photographed in succession with a small quartz spectrograph. This method enables us to secure a very good representation of the form of the absorption curve. The band at λ 2536 is seen to be extremely unsymmetrical. It widens out toward the red over a range of 400 Å.U., while its spread in the opposite direction is confined to a range not greater than 4 or 5 Å. U. Its widening is unsymmetrical from the very start, and in fact the spread toward the region of shorter wave-lengths becomes apparent only when the vapor has acquired considerable density. The temperature was well above a red heat at the end of the series, and the pressure was therefore several atmospheres. I mention this, as it proves that the effect of an atmosphere of hydrogen or air is not a mere *pressure* effect.

If the bulb is now opened and re-sealed, we obtain a series of spectra similar to those reproduced in Fig. 2. The band now widens symmetrically at first, reaching, however, a stage at which extension toward the region of shorter wave-lengths ceases. This symmetrical spread of the band is shown to still better advantage in Fig. 3.

This action of an inert gas in modifying the appearance of the absorption band was first observed in the photograph reproduced in Fig. 4. The fluorescence of the vapor was being studied by heating the metal in a quartz bulb provided with a long stem, in which the vapor was condensed. It was found in the first place that, if the stem was connected to an air-pump and the bulb exhausted, no fluorescence could be obtained, even though the metal was boiling briskly. On again admitting the air and repeating the experiment, a bright fluorescence was obtained.

Hartley, who first observed the fluorescence of the vapor, was of the opinion that it is necessary to have the vapor continuously formed—that is, the metal must be boiling and the vapor condensing on the walls—if continued fluorescence is to be observed. This may at first

sight appear to be true; for if we seal up a bulb and heat it far above the boiling-point of the metal, no trace of fluorescence appears. The cause of these apparently contradictory results was soon found. The reason why fluorescence does not appear when the bulb is connected to the air-pump and exhausted is that the vapor never acquires a sufficient density under these conditions. If we admit the air, the fluorescence does not appear until the metal has been boiling actively for ten or fifteen seconds, or until all of the air has been driven out of the bulb, which is then filled with pure vapor of mercury at a pressure of one atmosphere. A mixture of air and mercury vapor will not fluoresce, which explains the failure of the sealed bulb to show the phenomenon. If the bulb is first exhausted and then sealed, a very brilliant fluorescence is obtained.

The change in the appearance of the absorption band caused by the admixture of the air is very strikingly shown in Fig. 4. The spectra were taken in succession, the light of the spark having been passed through the quartz bulb containing the mercury. The flame which heated the bulb was gradually raised through the progress of the experiment. At first we have a mixture of air and mercury-vapor in the bulb, and the band broadens symmetrically. As the temperature rises and the boiling increases in violence, the air is gradually driven out of the bulb, the band actually *contracting* on the short wave-length side, notwithstanding the fact that the *vapor is actually becoming denser all the time.*

It was with a photograph taken in this way that the phenomenon was first discovered, the appearance being quite puzzling at first. The first explanation which occurred to me was that anomalous dispersion might have something to do with the phenomenon, for I had already made some experiments on the dispersion of the vapor at this point (photographs illustrating the effect at the band are reproduced in Fig. 5). In the first experiments the light from a small cadmium spark, after passage through the bulb, was brought to a focus on the slit of the quartz spectrograph. Under these conditions the effects described by Julius[1] might easily occur. Great care was therefore taken to exclude all possibility that dispersion might come into play. Small bulbs containing only a small speck

[1] *Astrophysical Journal,* 25, 95, 1907.

of mercury, which could be completely vaporized, were sealed up either exhausted or filled with air, and the light from the spark was allowed to pass through them into the slit without the intervention of a lens. The effect of the air on the appearance of the absorption band was the same as before.

As can be seen from Fig. 4, an apparent shift in the position of an absorption band may result from the admixture of a foreign vapor, the shift, however, being only of the order of magnitude of the width of the band. It seems quite possible that what takes place on a large scale in the case of mercury vapor may take place on a much smaller scale in the case of other absorption lines. In Fig. 6 the upper spectrum is of mercury *in vacuo;* the lower, of mercury in hydrogen.

Sufficient data have not been obtained to make it possible to formulate a theory of the action. The obliteration of the fluorescence by the presence of the air or other gas is very suggestive; for the same thing has been found in the case of sodium vapor, iodine, anthracene, and other fluorescent vapors. In the case of anthracene, one of my students, Mr. Elston, found that, while the fluorescence was destroyed by air, oxygen, sulphur dioxide, and other more or less chemically active gases, it persisted in nitrogen and hydrogen.[1] This lead me to believe that the action might be a sort of incipient chemical action.

I therefore tried mercury-vapor and nitrogen, but the action was the same. To reduce the probability that anything akin to chemical action was responsible, it seemed worth while to try the effect of helium. A bulb containing a drop of mercury was filled with helium for me by Dr. Adams, of Princeton, who happened to have a quantity of the gas on hand. The bulb was sealed at atmospheric pressure, and the absorption spectrum photographed. The appearance of the band was the same as in the case of the bulb filled with air.

It is, of course, of the greatest importance to determine the effect of increasing the pressure of the air, comparing the spectrum obtained with a very long tube filled with air at atmospheric pressure and mercury at, say, 5 cm partial pressure, with the spectrum of a short column of dense mercury-vapor, also mixed with air at 1 atmosphere. The effects observed when the pressure of the air is raised to several atmospheres must also be carefully studied. In all probability a

[1] *Astrophysical Journal*, 25, 155, 1907.

further spread of the band toward the region of shorter wave-lengths can be obtained by increasing the pressure of the inert gas in the bulb. Very likely the same result can be obtained with a very long tube with air at atmospheric pressure. In this way it will be possible to learn whether a given amount of the inert gas will affect only a given amount of the mercury vapor.

I have looked for a similar effect at the D lines of sodium, but thus far no evidence of an analogous shift has been observed. One of my students is at the present time engaged upon the study of the effect of inert gases upon the absorption spectrum of sodium. The appearance of the channeled absorption spectrum is profoundly modified, as I have already shown.[1]

THE JOHNS HOPKINS UNIVERSITY
June 7, 1907

[1] "Fluorescence and Magnetic Rotation Spectra of Sodium Vapor and Their Analysis," *Phil. Mag.*, (6) **12**, 499, 1906.

THE ABSENCE OF VERY LONG WAVES FROM THE SUN'S SPECTRUM[1]

By E. F. NICHOLS

During a visit to the Carnegie Solar Observatory in August, 1906, the writer set up a sensitive radiometer and reflected a beam of solar rays on five surfaces of rock-salt in succession. This procedure, according to the method of "residual rays,"[2] is known to give only a narrow spectral region, the mean wave-length of which is 510,000 Ångström units.[3]

The radiometer was of a type earlier described,[4] and the window which admitted the beams from the salt surfaces was a plate of quartz 0.5 mm thick, which has been shown to transmit about 60 per cent. of the energy in this part of the spectrum.[5]

The diagram (Fig. 1) shows the arrangement of apparatus. A beam of sunlight S reflected into the room from a silvered heliostat mirror fell upon a concave silvered mirror M_1 of 26 cm aperture and 75 cm focal length. The converging beam after leaving the mirror M_1 was reflected upon the five polished rock-salt surfaces s_1, s_2, s_3, s_4, s_5, in succession, of which the last surface s_5 was in focus of M_1. After leaving the surface s_5 the diverging pencil fell upon a small silvered collecting mirror M_2, and a secondary solar image was thus formed on one of the radiometer waves a. Exposures were made by raising and lowering a cardboard screen at A.

The solar beam was compared with one from an electric arc lamp L which, with its silvered converging mirror M_3, of 21 cm aperture and 100 cm focal length, could be moved into the position shown by the dotted lines. In this position a beam from the arc traversed the same path as the solar beam with which it was exchanged.

The beam from the arc caused a deflection of the radiometer suspension of 20 scale-divisions, but when a rock-salt plate $2\frac{1}{2}$ cm thick

[1] Contributions from the Solar Observatory, No. 19

[2] H. Rubens and E. F. Nichols, *Phys. Rev.*, **4**, 314, and **5**, 152, 1897.

[3] H. Rubens and E. Aschkinass, *Wied. Ann.*, **65**, 247, 1898.

[4] E. F. Nichols, *Phys. Rev.*, **4**, 298, 1897; *Astrophysical Journal*, **13**, 104, 1901.

[5] H. Rubens and E. Aschkinass, *loc. cit*, p. 249.

was interposed at *B*, no noticeable deflection could be detected. Rock-salt is very transparent to the region of the spectrum which comprises over 96 per cent. of the total energy emitted by the arc lamp, but is entirely opaque to the residual rays from rock-salt.

The test proved that over 99 per cent. of the energy of the beam under examination lay immediately in the spectral region about 510,000 Å. U.

The solar beam, however, gave a deflection of 17 scale-divisions, which was reduced only by 20 per cent. on interposing the test-plate. As about 10 per cent. of the reduction was due to the regular reflection at the two surfaces of the plate, not more than 10 per cent. could

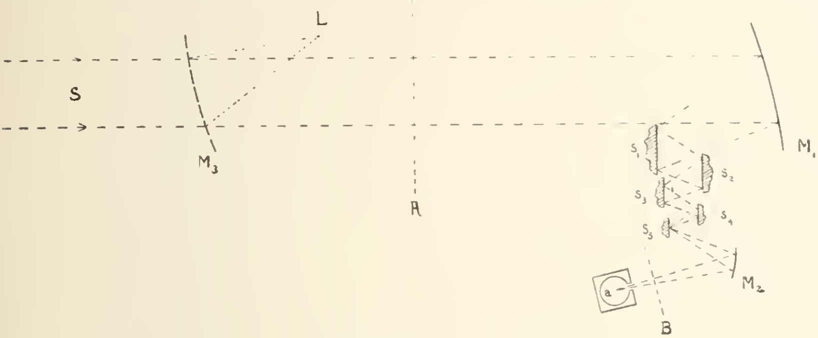

FIG I

be attributed to absorption proper. As the test-plate surfaces were poor, it is quite possible that no interior absorption took place. On this assumption the experiment shows that *no energy of a wave-length near 510,000 Å. U. reaches the earth from the sun.*

If, on the contrary, we assume that the questionable 10 per cent. was all due to absorption of long waves, and not to a scattering of shorter waves at the imperfect surfaces of the test-plate, several factors must be taken into account to get at the amount of long-wave absorption in the atmosphere. The approximation will necessarily be a rough one, based on the relative concentrations of the beams from the two sources compared, and their relative temperatures rated as ideal black bodies. In this way it appears that *the maximum atmospheric transmission for the rock-salt waves cannot be greater than 3 per cent.*

In 1897 Rubens and Aschkinass[1] found that the energy of a solar beam after four successive reflections on fluorite surfaces was reduced to zero, thus proving that the opacity of the combined solar and terrestrial envelopes was practically total for wave-lengths near 240,000. At the same time they studied the absorption of water-vapor between the wave-lengths 70,000 and 200,000 and found practical extinction at the latter wave-length. In a paragraph of a later paper, which had until recently escaped my notice, the same writers found water-vapor an absorber of the residual rays from rock-salt and sylvite.[2]

Thus we may assume that the absence of waves 510,000 long in the sun's spectrum to be due to aqueous absorption, even though the tests described in the present paper were made at an elevation of nearly 6,000 feet in a dry climate.

The rôle of water-vapor as an absorber in the earlier infra-red spectrum has long been known, and the later experiments indicate an enormous extension of the region in which the vapor is active. Furthermore, water still shows a strong absorption and some dispersion, even for the shorter electric waves ($\lambda = 6$ to 10 mm). Thus the range of absorption of water, liquid, and vapor is surpassed only among the metallic conductors.

I am greatly indebted to Director George E. Hale for his kindly and whole-hearted co-operation in the present work, and I am no less indebted to the kindness of Dr. Henry G. Gale for constant assistance during the course of the experiments.

Columbia University, New York
May, 1907

[1] *Wied. Ann.*, 64, 584, 1897.

[2] *Ibid.*, 65, 251, 1898.

EXPERIMENTAL TEST OF DOPPLER'S PRINCIPLE FOR LIGHT-RAYS[1]

By PRINCE B. GALITZIN AND J. WILIP

The first attempt to test Doppler's principle for light-rays in the laboratory was made by A. Bélopolsky.[2] For this purpose he constructed a special apparatus, consisting of two systems of light wheels coupled in pairs. Each pair carried eight mirrors mounted near the periphery of the wheels. Special electric motors set the two systems of eight mirrors in very rapid rotation in opposite directions. These wheels with mirrors were so arranged that a light-ray falling upon them would undergo several reflections from the silvered glass surfaces. By inclination of the direction of the incident beam the number of reflections could be varied at will.

If λ represents the wave-length of the incident ray, v_1 the linear velocity of the center of the mirror, V the velocity of light, and n the number of reflections, then, according to Doppler's principle, the wave-length of the incident beam after the nth reflection will have undergone a change $\delta\lambda$, which is represented with sufficiently close approximation by

$$\delta\lambda = \pm 2n\frac{v_1}{V}\lambda . \qquad (1)$$

If the systems of mirrors on the upper side of the wheels, where the reflection takes place, turn toward each other, the wave-length is shortened and the negative sign is employed; if the direction is opposite to this, the positive sign is used.

A detailed description of the apparatus and the method of its use in testing Doppler's principle is given in the communication by Bélopolsky cited above. Consequently we shall content ourselves with referring to that paper.

Bélopolsky used sunlight as the source of light in his investigation. For the dispersion in the spectrograph two compound prisms were

[1] Translated from *Bulletin de l'Academie impériale des Sciences de St. Pétersbourg,* (6) 1907, No. 8, May 1.

[2] *Bulletin de l'Academie des Sciences de St. Pétersbourg,* XIII, No. 5, 461, 1900; *Astrophysical Journal,* **13**, 15, 1901.

used. The photographic exposures were made in the region of the spectrum from λ 4380 to λ 4500. The displacement of several lines on each plate was measured; from these the mean displacement was deduced and then the corresponding velocity in the direction of the beam was computed.

Since the apparatus used by Bélopolsky possessed no very great dispersion, and the displacements were extremely small, even after the sixfold reflection which he employed, these measurements could make claim to no great accuracy. In fact, from the measurement of some lines the displacement was opposite to that expected from Doppler's principle, but nevertheless the mean value in every case gave a displacement which represented correctly the direction of rotation of the mirror.

Bélopolsky secured six different series of observations and compared the velocities derived with those obtained directly from the number of rotations of the wheels.

Considering the comparatively crude means with which the investigation was conducted, the agreement of the values may be considered quite satisfactory. With such dispersion only a skilful observer like Bélopolsky could obtain such good results.

Since Bélopolsky considered the investigation only as a first trial, it seemed to us very desirable to repeat the same experiment with more powerful means, employing the large Michelson echelon spectroscope of the Physical Laboratory of the Academy of Sciences, which possesses such a powerful dispersion. Bélopolsky kindly loaned to us the apparatus with the rotating mirrors, and with this we conducted a number of experiments which we now describe.

The theory of the echelon and the various methods of application of this valuable instrument have been worked out and examined by one of us,[1] and at that time its eventual application to the examination of Doppler's principle was spoken of. Consequently we refer to that paper in the discussion which follows.

We used an Arons' mercury arc lamp as the light-source. This was fed with a nine-ampere, but later thirteen-ampere, current from

[1] See Fürst B. Galitzin, "Zur Theorie des Stufenspectroscops," *Bulletin de l'Academie Impériale des Sciences de St. Pétersbourg*, V^e Série, T. XXIII, Nos. 1 and 2, p. 67, 1905.

the electric mains of the Academy of Sciences. After several successive reflections the beam was concentrated by the lenses upon the slit of the echelon spectroscope. Two mercury lines, that in the green at λ 5461 and that in the indigo at λ 4358, were photographed after passage through the echelon. For these exposures, the lower half of the collimator slit was first occulted by means of a screen mounted independently of the spectroscope, and an exposure was made with the mirrors rotating. Then the upper half was covered and a second exposure was made with the mirrors rotating in the opposite direction. The movement of the screen was so regulated that there was only a very small space between the ends of the two halves of the lines. After developing and drying the plates the displacement, $2\ \delta m$, of the two halves of the lines with reference to each other was measured under a microscope. $2\ \delta m$ is given in divisions of the head of the screw of the ocular-micrometer, a division of which is equal to $\frac{1}{400}$ mm. This displacement represented a double velocity in the direction of the light-ray.[1]

The exposures were always secured on the side of the echelon of the greater dispersion and in spectra of various orders. It is known that for one and the same line in neighboring orders of the echelon the difference in wave-length, $\Delta\lambda$, is independent of the order of the spectrum. If we represent the separation of the same lines on the photographic plate by Δm, the change in wave-length, $\delta\lambda$, corresponding to the displacement, δm, of the lines for the rotating mirrors relative to the stationary is expressed by

$$\delta\lambda = \delta m \frac{\Delta\lambda}{\Delta m}. \tag{2}$$

When $\delta\lambda$ is determined, the desired velocity can at once be easily computed. It is, regardless of sign,

$$v = \frac{\delta\lambda}{\lambda} V. \tag{3}$$

In this manner the velocity is expressed in terms of displacement of the lines.

The same quantity may be determined from the number of rotations per second of the wheels carrying the mirrors. Let r represent

[1] The ends of the half-lines lay so near to each other, that in the measurement of the displacement the influence of the curvature of the lines could be entirely neglected.

the distance of the middle of the small mirrors, each 2 cm wide, from the axis of rotation, and v_1 the linear velocity of the center of the mirrors, then

$$v_1=2\pi Nr\ .$$

At the nth reflection

$$v=2nv_1, \tag{4}$$

or

$$v=4n\pi Nr. \tag{5}$$

The test of Doppler's principle consists in comparing the values of v computed from the formulae (3) and (5).

The distance r was obtained by direct measurement. It is

$$r=0.112\text{ meter.}$$

A special speed-counter from a mercury interrupter was coupled with the rotating-mirror apparatus to determine the number of rotations N of the wheels corresponding to various exposures. The conversion factor was previously obtained by a series of experiments with a common revolution-counter and a Löbner second-counter which permitted hundredths of a second to be read off.

In all cases we sought to give the wheels the highest possible velocity. This was achieved with a current of about 7.3 amperes. The mean number of rotations per second varied for various series between $N=41.1$ and $N=46.2$, which represent linear velocities of the centers of the mirrors from 28.9 to 32.5 meters per second. During single series, for the same direction of rotation of the mirrors, N remained very constant.

Before the investigation was begun, the outer surfaces of the mirrors were carefully silvered by a special method.

The photographic exposures were made in part on Edwards' isochromatic plates and partly on Seed's extra-rapid plates.

At first we wished to photograph, together with the green and indigo-blue lines, the yellow line at λ 5791. But trial exposures showed that the exposure-time necessary to obtain sharp and well-measurable lines with the mirrors rotating was too long; and, since for long intervals of time we could not be sure of maintaining the echelon at sufficiently constant temperature—an indispensable condition in these experiments, as we shall presently see—the yellow line

was given up. Indeed the line turned out to be superfluous, for the green and indigo-blue lines belong to regions of the spectrum sufficiently widely separated to give a quite extended test of Doppler's principle.

The exposure-time for the two lines employed was varied for different photographs. The longer the exposure-time, just so much sharper are the lines, and just so much easier is it to measure the relative displacement. On the other hand, too long exposures are dangerous on account of the possible variation of temperature.

After successive exposures with rotating mirrors, exposures were always made with stationary mirrors, on another portion of the plate, in order to determine the dispersion, or the value of Δm, for the given position of the echelon.

The value of Δm need not be measured with great accuracy; nevertheless we give Δm as the mean of six or more measurements, three always being made by each of us.

The chief emphasis of these tests lay in the determination of $2\delta m$. Each value of δm given below is the mean of 20 single measurements, 10 by each of us. We may mention that the agreement of the single values in general is entirely satisfactory and in no case did we get a negative result, that is, a deplacement which is not in agreement with Doppler's principle in respect to the direction of rotation of the mirrors. On the contrary, the measured displacements, as we shall see further on, correspond very well with the values to be expected from Doppler's principle, in view of the admissible errors of observation. Most of the exposures were obtained with a fourfold reflection of the rays, but exposures were also made with six reflections.

Let us now consider a little more closely the influence of a possible oscillation of temperature on the results of these measurements.

It is evident in advance that a change of temperature can be very disturbing, for the echelon in a certain sense may be regarded as a very sensitive interference refractometer, and consequently each variation of temperature, which changes the height of the steps and the index of refraction of the glass, produces a wandering of the fringes. Let us see how great an error a change in temperature of $0^\circ.01$ C. will produce in the velocity v derived from the displacement of the lines.

In the paper cited earlier, "Zur Theorie des Stufenspectroscops" (p. 117) is found the formula

$$\delta\psi\frac{n_2}{r}\left\{\delta\mu+(\mu-1)a\delta\tau\right\}, \tag{6}$$

which gives the angular displacement of a spectrum line for a change of temperature $\delta\tau°$ C.

μ is the index of refraction of the glass for a given spectrum line; $\delta\mu$, the change of μ, when the temperature increases $\delta\tau$ degrees; a is the linear coefficient of expansion of the glass, = 0.0000085; n_2 and r are two quantities which are defined by the formulae (26) and (29) (*loc. cit.*). Let m be the linear distance in divisions of the head of the ocular micrometer of the microscope corresponding to the angle ψ, then we may make

$$m=A\psi,$$

where A is a constant, dependent on the properties of the optical train.

If $\Delta\psi$ is the angular distance between two fringes of adjacent orders, then

$$\Delta m=A\Delta\psi.$$

According to the formula (36) (*loc. cit.*)

$$\Delta\psi=\frac{1}{r}.$$

If for brevity we set

$$\delta\mu+(\mu-1)a\delta\tau=s, \tag{7}$$

then

$$\delta m=n_2\Delta ms.$$

δm is also the error in the measured displacement $2\,\delta m$, in consequence of a change of temperature $\delta\tau$.

We can therefore place

$$\delta(2\delta m)=n_2\Delta ms.$$

It follows from formula (2) that

$$\delta(\delta\lambda)=\tfrac{1}{2}n_2\Delta\lambda s,$$

or, from equation (3),

$$\delta v=\tfrac{1}{2}n_2\frac{\Delta\lambda}{\lambda}Vs. \tag{8}$$

This very simple formula permits the error in v to be computed directly.

From the numerical data which are given in the paper to which we have referred, and the values of $\delta\mu$ for flint glass for various spectrum lines (from the tables of Landolt and Börnstein), we compute the following values for the constants contained in formula (8), calculating δv for a temperature-change of 0°.01 C.

	Green Line	Indigo-blue Line
λ	5461	4358
$\Delta\lambda$	0.4766	0.2859
n_2	18277	22901
μ	1.5781	1.5918
$\frac{\delta\mu}{\delta\tau}$	0.00000396	0.00000556
s	0.0000000887	0.0000001059 (for 0°.01 C.)
δv	0.021 km	0.024 km

We see that a change of temperature of only 0°.01 C. affects the velocity by 21 to 24 meters per second. Hence if an echelon is to be used in actually testing Doppler's principle, the observer must exercise the utmost care to keep the temperature constant during both exposures with rotating mirrors.

In practice this is indeed quite a difficult matter and at first gave us much trouble, but finally we overcame the difficulties and obtained a quite constant temperature during the consecutive exposures. For this purpose the echelon-spectroscope with all the accessories was inclosed in a glass case, and the interior, where a change of temperature was most to be feared, was filled with cotton. A layer of cotton was also put on the cover over the echelon. In addition to this the whole was mounted in the basement of the main building of the Academy of Sciences where the daily oscillation of temperature is very small, and here the windows were covered. A very sensitive thermometer, divided in fiftieths of degrees, whose bulb was near the echelon, gave extremely small variations. In spite of this the observations commonly had to be confined to the morning hours only, when the sun had not yet shone around the corner of the building; and even then only one line (two consecutive exposures) could be investigated on one and the same day because the air of the laboratory became disturbed by the rotation of the mirrors, as was indicated on the thermometer after a time. A small change of temperature at

the beginning of the observations is not so dangerous, because the poor conductivity of the glass makes it probable that the echelon assumes this temperature much later. But if the investigation is pushed farther one cannot be sure of the conditions of temperature in the echelon. In no case was the measured temperature-change greater than from 0°01 to 0°02 C., with a single exception where the change amounted to $3\frac{1}{2}$ hundredths.

By observing all these precautions, the results obtained were very satisfactory, as will be recognized in the summary of the investigation given below.

The numerical results are given in the following tables, I and II. The first gives the cases of fourfold reflection, the second of sixfold.

The first column gives the date of the observation; the second, the emission line employed; the third, the rotation number N. It should be remarked that N is the mean of four readings made at the beginning and end of the two consecutive exposures. The fourth column gives the exposure-time for each plate; the fifth the displacement sought (moving mirror relative to stationary mirror) in divisions of the head of the ocular micrometer ($2\delta m$, the sum of the two displacements, was measured directly[1]). The sixth column gives the value of Δm, that is, the distance of the two bands in neighboring orders, likewise in divisions of the head. The values of $\frac{\Delta\lambda}{\Delta m}$ are collected in the seventh column. These quantities give a measure of the dispersion of the apparatus; that is, the number of Ångström units corresponding to a division of the micrometer-head. In the eighth column are the velocities derived from the observations. The ninth gives the velocities computed by the number of rotations per second, N. Finally, the last column gives the difference Δv of these values $\{v$ (from number of rotations) $- v$ (from displacements)$\}$.

With reference to the determination of v from the number of rotations per second N, it should be stated that we undertook to mount the mirrors so that the rays reflected from the center of the mirrors, while the reflecting surface was parallel to the slit, should coincide as closely as possible with the middle of the slit, where the

[1] It is to be remarked that, in order to vary as much as possible the conditions of the experiments, the investigations were begun at one time with one direction of rotation, the next time with the opposite direction.

TABLE I

Date	Line	N	Exposure	δm	Δm	$\frac{\Delta\lambda}{\Delta m}$	v from Displacement	v from No. of Rotations	Δv
			mins.	divs.	divs.		km. per sec.	km. per sec.	km. per sec.
April 10......	Green	45.1	15	4.75	524.9	0.000908 Å. U.	0.237	0.254	+0.017
" 11......	Green	45.4	15	5.28	559.6	852	0.247	0.256	+0.009
" 12......	Indigo-blue	46.2	30	6.24	399.3	716	0.308	0.260	−0.048
" 15......	Indigo-blue	45.9	60	4.80	403.1	709	0.234	0.258	+0.024
" 16......	Green	45.3	30	5.11	564.4	845	0.237	0.255	+0.018
" 17......	Green	45.4	30	5.16	567.3	840	0.238	0.256	+0.018
" 18......	Indigo-blue	45.5	50	6.02	429.3	666	0.276	0.256	−0.020
						Means	0.254	0.256	

TABLE II

Date	Line	N	Exposure	δm	Δm	$\frac{\Delta\lambda}{\Delta m}$	v from Displacement	v from No. of Rotations	Δv
			min.	divs.	divs.		km. per sec.	km. per sec.	km. per sec.
April 20......	Green	45.0	60	7.60	491.0	0.000971 Å.U.	0.405	0.379	−0.026
" 21......	Green	44.0	60	6.68	490.1	973	0.357	0.372	+0.015
" 22......	Green	41.1	60	6.27	495.4	962	0.331	0.346	+0.015
						Means	0.364	0.366	

displacements are measured. In the computation of v, from formula (5), we have taken for r the distance of the center of the mirrors from the axis of rotation. If the reflection had taken place on one of the edges of the mirrors, the computed velocity would have been in error about 10 per cent.

When we consider the results in these two tables we see that the difference between the velocity v computed from the displacement and from the number of revolutions amounts in the mean to only about twenty meters per second.

Considering the difficulty of these measurements and the influence of variation of temperature mentioned above, the agreement can be considered as entirely satisfactory. Therefore, Doppler's principle for light-rays is, within the permissible range of error of observation, fully confirmed.

Minor Contributions and Notes

A PHOTOGRAPHIC STUDY OF THE SPECTRUM OF *SATURN*[1]

During the autumn of 1905 I photographed the spectrum of *Saturn* for the purpose of investigating the absorption of the planet's atmosphere. Plates specially sensitized to the orange-red were used. With these plates the spectrum was photographed as far down as to Fraunhofer's C. Since low dispersion is most effective in depicting faint bands, such as are found in the spectra of the planets, a single-prism spectrograph was employed.

The slit of the spectrograph was set upon the major axis of the Saturnian system, and the spectra of the ansae of the rings appear on the plates above and below the spectrum of the ball of the planet. The moon served as a source for the comparison spectrum, the two parts of which lie outside the spectra of the rings. In these relative positions the spectra from the different sources may readily be compared, and thus the detection of faint bands be facilitated.

The moon was photographed at about the same altitude as *Saturn*, so the absorption due to the earth's atmosphere affected equally both spectra. The solar light reaching the earth by reflection from the moon has the same spectrum as direct sunlight, and also the same as the sunlight that reaches *Saturn*. Therefore, if light from *Saturn* shows a different spectrum from that of the moon, these differences must be produced by selective absorption (and reflection) in the atmosphere of *Saturn*.

For this investigation of *Saturn's* spectrum, which is similar to the one made on the spectrum of *Jupiter*, published in *Bulletin* No. 16, a series of about ten photographs were made. Examination of these plates, under low magnification, revealed several absorption bands in the region between the Fraunhofer lines F and C. Three of the plates have been measured for the wave-lengths of the bands. The results of the examination and the measurements are summarized in the following table:

[1] *Lowell Observatory Bulletin* No. 27.

Wave-Length	Remarks
5430	Band in *Saturn*—not seen in rings. It is visible on all the plates as a fairly strong band.
5592	There is a suggestion on some of the plates that the solar band here may be strengthened by absorption in *Saturn*. However, this can be only slight. The same effect is noticeable on the plates of *Jupiter*.
577	Some of the plates indicate that *Saturn* has here a weak band which seems to cover the region between the solar bands at λ 5758 and λ 5785.
6145	There appears, on most of the plates, a narrow band here in *Saturn*. Although there are solar lines near, it is doubtful if they produce the band.
6193	A very strong band—the strongest one in the spectrum of *Saturn*. No trace of it is seen in the spectra of the rings. It is broad and symmetrical, and is traceable to the band at λ 6145.
645	Near the middle of a broad ill-defined band in *Saturn*.
6563	The solar line C. As far down as the spectrum can be examined.

In relative strength these bands stand in the following order:

λ	
6193	
5430	
6145	
645	
577	(Weak and doubtful.)

It is an interesting fact that none of the bands observed in the spectrum of *Saturn* has been seen in the spectra of the rings. That the faint ones have not been seen could be due to the difficulty of observing weak bands in spectra as narrow as those of the rings, but a band much weaker than the one at λ 6193 would be apparent. The absence of this heavy band from the rings shows that, if they possess an atmosphere at all, it must be much rarer than that surrounding the ball of the planet. The absence of this band from the ring spectra was observed visually by Keeler and photographically by Hale and Ellerman.

It should also be remarked that none of the absorption bands in the spectrum of *Saturn* can be identified with those bands due to absorption in the earth's atmosphere. My spectrograms show no trace of aqueous vapor absorption in *Saturn*.

A fivefold direct enlargement of one of the plates of *Saturn* is reproduced in the accompanying plate, together with similar direct enlargements of plates of *Jupiter, Uranus, and Neptune*. A table is also

Band Near	Saturn		Jupiter		Uranus[1]		Neptune[1]	
λ	λ	Remarks	λ	Remarks	λ	Remarks	λ	Remarks
486					4861	F, stronger and broader than in Sun.	4861	A narrow, strong band.
510					5101	A weak band	5104	A strong band.
523							5225	Broad, weak band.
541			5406	Blue component, which is largely solar.	5404	Increased absorption; there are strong solar lines at this place.	5396 5408	Slight local absorption probably due to pair of solar lines.
							5425	A secondary maximum in the strongest band in the spectrum.
543	5430	A fairly strong band	5427	Yellow component, which is largely Jovian.	5427	Maximum of strongest absorption band in spectrum.		
							5432	The point of maximum intensity of this band.
559	559	A suggestion of absorption.						
577	577	What seems to be a weak band covering the region between the solar lines at 5759 and 5786.	5755 (5769) 5783	Green component. Center. Orange component.	5755 (5769) 5783	A first maximum in second strongest band in spectrum. A second maximum in this strong band	5771	Point of maximum intensity of violet (and stronger) component of band.
							5780	Maximum of red (and weaker) component.
602			6023	Weak and doubtful.				
615	6145	A narrow band.						
619	6193	The strongest band in this planet. It is not in the rings.	6192	Strongest band in spectrum.				
647	645	Near the middle of a broad, ill-defined band.	6437 (6465) 6495	Orange edge of bd. Center of band. Red edge of band.		(*Uranus* not photographed below D.)		(*Neptune* not photographed below D).

[1] *Lowell Observatory Bulletin* No. 13

added here showing in parallel columns the results of the study of the spectra of the four planets.

From a comparison of these plates and an inspection of the table it will be evident that the planets which are telescopically similar have similar spectra: the spectrum of *Jupiter* is similar to that of *Saturn*, while the spectrum of *Uranus* is more like that of *Neptune*. However, the bands at λ 543 and λ 6193 are stronger in *Saturn* than in *Jupiter*, whereas the band at λ 646, which is of considerable strength in *Jupiter*, is weak in *Saturn*. These disagreements suggest a difference in the relative proportions of the gases in the atmospheres of the two planets.

The spectrum of *Uranus* differs from those of *Jupiter* and *Saturn* in the increased strength of the bands at λ 543 and λ 577. In it the hydrogen line F is of increased strength and it contains in addition other faint bands not seen in *Saturn* and *Jupiter*. The comparison spectrum of the *Uranus* plate is that of *Saturn*, but as the exposure was not suited for bringing out the bands in *Saturn*, the plate cannot serve for comparing directly the two spectra. On this plate the spectra do not extend below the D lines.

The plate of *Neptune* shows the spectrum of this planet to contain many strong absorption bands. These bands are so pronounced in the part of the spectrum between the Fraunhofer lines F and D as to leave the solar spectrum unrecognizable. An iron-sodium spark and the solar type-star *β Geminorum* were photographed on this plate for comparison. The star spectrum lies above and below that of the planet, and has on its outside borders and extending beyond it the bright *Fe* and *Na* spark lines. *Neptune's* spectrum is strikingly different from that of *Uranus*, the bands in the latter planet all being reinforced in *Neptune*. In this planet there are also new bands which have not been observed in any of the other planets. The F line of hydrogen is remarkably dark. As has been stated before, this band is of more than solar strength in the spectrum of *Uranus* also. Thus free hydrogen seems to be present in the atmospheres of both these planets. This and the other dark bands in these planets bear evidence of an enveloping atmosphere of gases which is quite unlike that which surrounds the earth.

V. M. SLIPHER

JUNE 1906

PHOTOGRAPHS OF THE DOPPLER EFFECT IN THE SPECTRUM OF HYDROGEN AND OF MERCURY. REJOINDER TO MR. HULL'S REPLY

I recently published in this *Journal* some remarks on a paper by Mr. G. F. Hull on the Doppler effect for canal rays. Mr. Hull's reply to these remarks does not seem to add clearness in regard to the question at issue; and as the matter seems to me important, it is probably best for me to publish my spectrograms as an answer to Mr. Hull's statements.

The three spectrograms of Plate VII were obtained with a Rowland concave grating of one meter's radius. The hydrogen lines of Fig. 1 were photographed in the second order; the lines of the other two spectrograms belong in part to the second, and in part to the third order of the mercury spectrum. In the case of hydrogen as well as of mercury, the canal rays moved toward the slit.[1] It will be seen that in both cases we obtain the lines at rest in their normal position; and simultaneously, on the side toward the ultra-violet, the Doppler effect —that is, a band of movable lines which were emitted with a different velocity by the particles of the canal rays. Between the unmoved and the moved lines lies a maximum of intensity.

The occurrence of the minimum of intensity—that is, the lack of an emission of light at a small velocity of translation—excites a great theoretical interest. Its breadth also gives a measure of the magnitude which the cathode-drop must have in order that the canal rays should assume so large a velocity that the movable intensity should become appreciable, hence that the Doppler effect should be obtained.

A second point of importance in judging as to the statements of Mr. Hull is the ratio of the movable intensity to the stationary intensity. The reproduction of the spectrograms will doubtless permit us to see that this ratio is large for hydrogen, but small for mercury lines. These also further exhibit very large differences among themselves, the ratio being the largest for the line at λ 2537, smaller at λ 4047, and very small at λ 4078. As I have already shown elsewhere, the movable intensity has its direct origin in the translation

[1]The reproductions were made from glass negatives which were contact copies obtained without any retouching. The original negatives were intensified with uranium, whence the coarseness of the silver grains.

of the particles of the canal rays; the stationary intensity probably comes to the point of emission at the separation of the negative electrons from neutral atoms, hence at the development of positive atomic ions ("Atomionen"). This ionization may be accomplished by the canal rays themselves, or by the secondary cathode rays which are produced from the canal rays according to the observations of J. J Thomson and Chr. Füchtbauer. It is a fact that for canal rays the stationary intensity is small, while it is large for canal rays in mercury vapor. This may be related to another phenomenon, namely, the fact that the slow cathode rays of the positive column of light of the glow-discharge at lower temperature brings the series-lines of mercury into more intense emission, but the series-lines of hydrogen only to a faint emission. By diminution of the absorption of the canal rays and the cathode rays in the space around the gas, or by the reduction of the gas-pressure, the stationary intensity in the spectrum of the canal rays may be diminished. The movable intensity can be increased by enlarging the velocity of translation.

In his reply Mr. Hull writes:

> Professor Stark suggests that it is necessary to satisfy the conditions that the cathode-drop producing the canal rays shall not be less than a certain limiting value. The inference is made that Professor Stark has found that limiting value. It certainly would have made for definiteness of our ideas if Professor Stark had given us the limiting values for hydrogen and mercury.

If Mr. Hull had attentively read my detailed paper which appeared in the *Annalen der Physik* in November 1906, his remark just quoted would have been superfluous, for I published the limiting values which the cathode-drop must exceed in order that the Doppler effect should be demonstrable in the hydrogen series, and for the mercury lines. It amounts for the hydrogen lines to about 700 volts, as Mr. Hull may see if he reads the article again, while it is of different magnitudes for the *Hg* lines—for λ 2537, 8000; for λ 4047, 7000; for λ 4078, 15,000 volts. I also gave approximate data as to the ratio of the movable intensity to the stationary intensity of the series lines produced by the canal rays. Table VIII of my paper shows how greatly this ratio depends on the gas-pressure and the cathode-drop. In referring to this table I should also like to make the following remark: If Mr. Hull is of the opinion that it is very easy to demon-

strate the Doppler effect for hydrogen, I agree with this view, and add that it is much easier still in case of mercury and helium to obtain the stationary lines from their canal rays without any indication of the Doppler effect.

Mr. Hull appears to attach more value to his negative results than to my positive results. Hence I may point out that Professor F. Paschen also obtained the Doppler effect for the *Hg* lines. He wrote me, in a letter dated November 10, 1906: "I have also obtained the Doppler effect in mercury at high potential;" and in a letter dated February 12, 1907, he says:

> I shall hardly publish my observations on mercury. If the Doppler effect is observable in mercury, I should have to see to it that I could satisfy the appropriate conditions for other cases. I contented myself with seeing the effect at λ 5461, and photographing it for several other lines. These observations were made only for my own information, and are not comparable with your extensive results, so that I should have to continue mine further if I wished to publish anything about them.

I suspected that Mr. Hull was unsuccessful in his search in case of mercury as well as helium, for the reason that the movable intensity is very small in comparison with the stationary intensity for the helium lines also. This is in fact the case, and Dr. Rau, of Braunschweig, has meanwhile succeeded in demonstrating the Doppler effect for the canal rays in helium. The reason for the predominance of the stationary intensity probably will also be related to the fact that the slow cathode rays in the positive column of light of the glow-discharge at low temperature bring the series lines of helium into intense emission.

As an explanation of the negative results of his experiments, Mr. Hull has advanced the hypothesis that the absence of the Doppler effect in mercury and helium is occasioned by the presence of other non-luminous particles, probably those of hydrogen, which are easily set in motion. This hypothesis is contradicted by the following fact: The Doppler effect is to be observed for quick canal rays in case of the mercury and helium lines, whether a considerable amount or only an extremely small amount of hydrogen is admixed with these gases.

J. Stark

Hannover
May 10, 1907

ARE LUMINOUS METALLIC PARTICLES THROWN OUT FROM THE POLES IN THE SPARK DISCHARGE?

Professor Schuster's criticism[1] of my article published in the January number of this *Journal* is due in part to a misinterpretation of my views. For this misinterpretation I feel that I am partly responsible, for upon again looking over those two sentences which he so severely criticizes I find that they are not satisfactorily worded. In them I tried to condense a rather extended argument, with a resulting loss in clearness. But had Professor Schuster, or the person of whom he speaks as having quoted me, read my entire article, he would have found that I have not taken as positive a stand as he credits me with. I have never made the general statement "that metal particles of mercury and cadmium volatilized by the spark do not travel at a higher rate than 100 meters a second." What I have stated is that for a 3 mm spark-gap between *Cd-Hg* electrodes with no (or very small) capacity in circuit there is no motion of the luminous particles as great as 100 cm per second—if we base our judgment upon the four lines measured.

When a medium-sized Leyden jar was inserted in multiple with the spark-gap, there were rather large discrepancies in my measurements. One reason for these discrepancies may be found in the fact that when an image of the spark placed parallel to the slit is focused upon the slit, the lines appear quite uneven—an unevenness which is in part due to differences of intensity, but in part apparently to different breadths of the lines in different parts of the spark-gap. The results therefore were more or less in doubt, but there did not seem to be any Doppler effect—certainly not an amount as great as one would expect from the Schuster-Hemsalech experiment. All of my data, taken together, suggested that "another interpretation may be given to their results" (p. 2 of my paper). The alternative hypothesis was then advanced, viz.: that the curving of the images of the spark-discharge seen in a rotating mirror is due to the propagation of a condition of luminosity in the direction of the discharge.

The argument by means of which Professor Schuster feels that he has established the certainty of the motion of the luminous metal

[1] *Astrophysical Journal*, **25**, 277, May 1907.

particles is one which everyone thinking about the phenomenon, I presume, has constructed for himself. There is no question about metal particles being given off from the electrodes. They must be given off whether capacities are used or not. Let us assume that the curving of the images in the Feddersen experiment is due to the motion of luminous metal particles. Then for the most part only those particles which are freshly driven out during any oscillation of the discharge are luminous, the vapor product of previous oscillations apparently taking but a small part in the discharge. If this diffusion of vapor is necessary for successive oscillations, one would expect that it would be necessary in the prolonged discharge of a coil. Hence I expected to find a Doppler effect in the spark even when capacities were not inserted. Since I found no such effect, with or without capacities, I was led to question the hypothesis of moving luminous particles.

But is the rotating mirror device an accurate analyzer of the spark phenomenon? I do not feel that we can place absolute confidence in the visual evidence it affords. For example, cathode rays streaming through helium excite the molecules of that gas so that they radiate the green-blue line λ 5016. If it were possible to analyze, by a rotating mirror or film, the motion of a rapidly interrupted cathode stream, or if we were to base our conclusions upon the magnetic or electrostatic deflections of this stream, we might conclude, were we ignorant of the nature of the cathode rays, that the stream consisted of particles of helium moving with a great velocity. Indeed, Professor Schuster, in 1890, basing his argument, not upon the above grounds of course, but upon a more or less obvious hypothesis, proved that the negatively electrified particles proceeding from the cathode in a tube filled with nitrogen were atoms of that gas. It remained for other investigators, guilty at the time of bold extrapolation in the construction of a hypothesis, to make the notable discovery of the electron. Evidently infallibility does not always lie on the side of the obvious hypothesis.

The canal stream in helium illustrates my point rather well. I have been unable to find a motion, except a rather small one, of the luminous helium particles. Yet experiments which I have made this

past winter show that magnetic and electrostatic deflections of the stream (with exceptions to be noted in a later paper) are obtained of the same order as those observed for the hydrogen canal stream. Apparently particles of the size of hydrogen atoms, not luminous, are moving through the helium vapor, lighting it up on the way. Evidently the only test whether the luminous particles are in motion or not lies in the presence or absence of the Doppler effect. And if a genuine Doppler effect should be found for the spark-discharge, there would be no question about the luminous particles being in motion.

The review of my article in the last *Beiblätter* (No. 12, 1907) calls my attention to a paper by Hagenbach[1]—a paper which I had entirely overlooked. Hagenbach, using capacity and self-induction in circuit with a spark-gap of 2 to 8 mm between zinc and aluminum, found no Doppler effect when an echelon prism was used as analyzer. With a concave grating he found 0.007 tenth-meters as a superior limit to the Doppler effect. The corresponding velocity is given as 280 meters per second. With zinc and cadmium electrodes he found a smaller velocity.

I have given 100 meters per second as a superior limit to the velocity of the luminous particles in the *Cd-Hg* spark-gap when no capacity was used. With capacity the discrepancies were two or three times as great, so that a superior limit would be about 250 meters per second. The agreement with the results obtained by Hagenbach is very close.

Hagenbach points out that the velocities deduced from his measurements are not at all in accord with those obtained by Schuster and Hunsalech and Schenck. The last observer deduced a velocity of 5,000 meters per second for the luminous particles—a velocity twenty times as great as the possible velocity deduced from the Doppler effect. Hagenbach suggests that the metal vapor may be thrown from the electrodes with great velocity and then brought to a luminous condition by the successive oscillations. "Es ist möglich dass bei jeder Oszillation neuer Metalldampf dazu kommt, doch hauptsächlich wird der schon vorhaudene mitleuchten, ohne wesentliche mechanische Verschiebung." In other words, he believes that, for

[1] *Annalen der Physik*, 13, 362, 1904.

the most part, the luminous particles are not in motion. But he does not account for the curving of the images of the successive oscillations when viewed in a rotating mirror. That phenomenon must be due either to a motion of the luminous particles or to the propagation of a condition of luminosity. His results, as well as my own, are not in accord with the first hypothesis. The rotating mirror experiment does not contradict the second.

G. F. Hull

Dartmouth College
Hanover, N. H.
July 4, 1907

VENUS AS A LUMINOUS RING

The observation of this rare phase of *Venus*, made by one of us in 1898,[1] was repeated by the other at the conjunction of 1906, the observer's notes being as follows:

> On 1906 November 29, $5^h\ 7^m$ G. M. T., *Venus*, being about 1°49′ from the sun's center, was observed with the 5-inch finder of the 23-inch telescope. In moments when the air was steady the complete outline of the planet was distinctly seen. On the side nearest the sun it was bright and easily visible, but on the opposite side it was very faint and could be seen only for a few seconds at a time.
>
> When the complete circle was seen, the space within it always seemed a shade darker than that without. I suspect, however, that this was a subjective effect, as it was not noticed when the fainter part of the ring disappeared through bad seeing. No other marked peculiarities were noticed, though a bright spot was several times suspected in the bright part of the ring.
>
> The sky was very clear and blue. There was a strong wind from the northwest. The seeing was generally poor, but at times it was fair and steady for a few seconds. The whiteness of the field varied noticeably from time to time.

The planet was also observed on November 27 and December 4, and the extent of the crescent measured with a filar micrometer. Bad weather prevented further observations.

Reducing the results by the formulae of the paper already referred to, we obtain the following values for the extent of the twilight arc in the atmosphere of *Venus*.

[1] H. N. Russell, *Astrophysical Journal*, 9, 284, 1899.

Date, 1907	Observer	Seeing	Apparent Elongation of *Venus* from Sun v	Prolongation of Each Cusp p	Twilight Arc s
Nov. 27 . .	H. N. R.	Poor	4° 33′	20°	58′
Nov. 29. . .	Z. D.	Fair	1 49	90	>62
Dec. 4. . . .	H. N. R	Very bad	7 14	10.5	45

The last value is clearly too small, owing no doubt to the very bad seeing, which would render the delicate extremities of the cusps invisible. The other values agree fairly well with the mean value 70′ found in the earlier discussion.

The ring-phase of *Venus* may perhaps be seen again in 1914, if the atmospheric conditions are very favorable. There will be no other opportunity until 1972.

HENRY NORRIS RUSSELL
ZACCHEUS DANIEL

PRINCETON UNIVERSITY OBSERVATORY
June 3, 1907

A GENERAL INDEX TO THE ASTROPHYSICAL JOURNAL

The preparation of an index to the first twenty-five volumes of this Journal, covering the twelve and one-half years from January, 1895, to June, 1907, is now under consideration. Such an index would doubtless prove of great convenience to the workers in astrophysics and to libraries. The possibility of its publication will depend upon the number of advance orders received. If 200 subscriptions are obtained, the index can probably be issued at a cost of about $1.50; if 300 advance orders should be given, the work will certainly be undertaken, with the expectation of its publication in the autumn of 1907, and the price will probably be somewhat less than $1.50.

All subscribers and librarians who would purchase such an index, if issued, are therefore requested to notify the publishers at once by postcard of the number of copies for which they will subscribe.

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In the department of *Minor Contributions and Notes* shorter articles will generally be placed and subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right-unless the author requests that the reverse procedure be followed.

Accuracy in the proof is gained by having manuscripts type-written, provided the author carefully examines the sheets and eliminates any errors introduced by the stenographer. It is suggested that the author should retain a carbon or tissue copy of the manuscript, as it is generally necessary to keep the original manuscript at the editorial office until the article is printed.

All drawings should be carefully made with India ink on stiff paper, usually each on a separate sheet, on about double the scale of the engraving desired. Lettering of diagrams will be done in type around the margins of the cut where feasible. Otherwise printed letters should be put in lightly with pencil, to be later impressed with type at the editorial office, or should be pasted on the drawing where required.

Authors will please carefully follow the style of this *Journal* in regard to footnotes and references to journals and society publications.

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THE

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ABSORPTION AND EMISSION SPECTRA OF NEODYMIUM AND ERBIUM COMPOUNDS

By JOHN AUGUSTUS ANDERSON

INTRODUCTION

Of the eighteen or twenty elements belonging to the group of rare earths, seven or eight are of special interest to spectroscopists on account of their absorption phenomena. These are neodymium, praseodymium, erbium, holmium, samarium, dysprosium, thulium, and europium. The absorption spectra of solutions of these are remarkable on account of the number and relatively small width of the bands they present, some of which, notably the one near λ 4270, in the aqueous solution of some of the salts of neodymium, may very reasonably be spoken of as lines. These spectra have been the subject of a great number of investigations, a good summary of which may be found in the third volume of Kayser's *Handbuch der Spectroscopie.* In general it may be stated that the solutions of different salts of the same element show very similar absorption spectra, especially when conditions as to concentration and thickness of solution are the same.

The absorption spectra of the crystallized salts of some of these elements have been studied by a number of investigators, the most important work having been done on the crystals of various "didymium" salts by Henri Becquerel.[1] He found that the absorption of

[1] *C. R.*, **104**, 1691–1693, 1887; *Ann. Chim. et Phys.* (6), **14**, 257–279, 1888.

any given crystal depends, to some extent, upon the direction in which the light traverses it, the variation being, however, one of intensity and not of position of the bands. The crystals of different salts, as a rule, show different spectra, in speaking of which he says: "In passing from one spectrum to another, it may be seen, for example, that a given band is displaced, while neighboring bands are not; sometimes a series of bands moves as a whole, while other series are unaffected, ... finally, some bands, present in one case, may be entirely absent in another." He seems to find in this evidence in favor of the view held by many chemists, that "didymium," or its components, neodymium and praseodymium, are in reality a complicated mixture of several substances, for after comparing the spectra of the crystals with those of their corresponding solutions he says: "In general it may be stated that the spectra of all solutions differ very little from each other, while those of the crystals are quite different. It seems, then, that the matter forming didymium, when in solution is brought into the same condition, and that the presence of different acids in this condition has little or no influence on the absorption."[1] Becquerel also observed that, in case of the dry salts of "didymium," absorption spectra could be observed in white light diffusely reflected from them. The spectra thus observed he found to behave in a way very similar to those observed in crystals.

When the oxides or phosphates of some of these elements, notably erbium and neodymium, are heated to incandescence in a non-luminous flame such as that of a Bunsen burner, the spectrum emitted is not continuous, as in case of most solids and liquids, but consists of some bright bands superposed upon a comparatively faint continuous background. This was first observed in 1866 by Bahr and Bunsen[2] for the oxide and phosphate of erbium, since which time it has been found that the oxides of neodymium, holmium, and perhaps other elements show similar emission spectra, although they are not as brilliant as that of erbium. Bahr and Bunsen concluded that the emission of the oxide and phosphate of erbium is the same, noting, however, that the bands are more intense with the phosphate. They further concluded that the positions and relative intensities of the

[1] *Ann. Chim. et Phys* '6 , **14**, pp. 257 ff.

[2] *Liebigs Ann.*, **137**, 1–33, 1866.

bands agree with those of the absorption bands seen in the solutions of erbium salts. Thalén[1] in 1880 came to the same conclusion in regard to the agreement between the bands in the absorption and emission spectra of erbium. Lecoq de Boisbaudran[2] investigated the emission as well as the absorption of both erbium and neodymium, and found that the emission of erbium phosphate differs considerably from that of its oxide. That this difference was not due to impurities was evident from the fact that both the compounds were made from the same preparation, namely from a solution of erbium nitrate. He also compared them with the absorption spectrum of the chloride, and his drawings show that the agreement is rather poor. About all that can be said is that the two show bands in approximately the same regions of the spectrum, but that they differ considerably both as to intensity and more exact position.

OBJECT OF PRESENT INVESTIGATION

The present investigation was undertaken for the purpose of determining:

1. Whether the emission bands of incandescent erbium oxide really come from the solid itself, or whether they are due to some gaseous layer very close to its surface.

2. How the three kinds of spectra given by some of the elements of the rare earths are related to each other. The three kinds of spectra are:

a) Absorption by solutions of the salts.

b) Absorption by diffuse reflection of white light from the solid compounds.

c) Emission by their incandescent oxides or phosphates.

The elements, erbium and neodymium, were selected partly because the absorption spectra of their solutions show a greater number of bands than those of the other elements, and also because both are known to show very well all three types of spectra mentioned above.

APPARATUS AND METHODS

1. *Salts and solutions.*—The salts and solutions of neodymium were all made from the double nitrate of ammonia and neodymium,

[1] *Comptes Rendus*, **91**, 326–328, 376–378, 1880.

[2] *Spectres Lumineux*, Paris, 1874.

a quantity of which was kindly furnished to Professor H. C. Jones for this and other work by the Welsbach Company of Gloucester, N. J. The anhydrous chloride, sulphate, and nitrate used in making the spectrograms shown in Figs. 8 and 9 were prepared by Professor Renouf, while all the other salts and solutions used were prepared by the author, the procedure being as follows: The double salt was first precipitated by oxalic acid, and the oxalate washed thoroughly with hot water, after which it was dried and heated to a bright red until completely transformed into the bluish-gray oxide Nd_2O_3, a considerable quantity of which was prepared and kept on hand. From it the sulphate, chloride, nitrate, and acetate were made by simply dissolving it in the corresponding acid.

The erbium preparations used were all made from material which Professor Rowland prepared while he was interested in the separation of the rare earths. It will be remembered that while he was working on the identification of the lines in the solar spectrum he found it difficult or impossible to obtain many of the elements belonging to the group of rare earths in a state of sufficient purity for his purpose. On this account he decided to commence with the original minerals containing these elements, and make an attempt at separating the elements himself, using purely spectroscopic means to guide him in the work. Among the preparations left by him were about a dozen small bottles labelled Erbium "A," Erbium "B," etc., each one containing from two to five grams of oxide. Professor Rowland's notes do not give any definite information about the meaning of the designations on the labels, and hence the contents of each bottle was dissolved in HCl and made up so that all the solutions had, as nearly as possible, the same concentration. On examining the absorption spectra they were all found to be identical as far as the positions and relative intensity of the bands was concerned, but they showed some variation in absolute intensity. The examination of the spectra showed that the solutions were quite free from neodymium and praseodymium, the merest trace of the yellow band of neodymium appearing only when a syrupy solution six or more centimeters deep was used. The bands of holmium, if present at all, were not very strong, indicating that the impurities were chiefly such as give no absorption spectra, and accordingly would, in all probability, not interfere seriously

with the work of the present investigation. The preparations showing the strongest absorption bands, and hence containing the least amount of non-absorbing impurities, were selected and used in the work.

2. *Spectroscopes and photographic plates.*—For visual examination of the spectra, a small direct-vision spectroscope by Steinheil, containing a train of five prisms, was used; while for photographic purposes, a concave grating spectroscope was employed. The grating is a $2\frac{1}{2}$-inch, of 1 meter focus, ruled with 15,000 lines to the inch.

Since both neodymium and erbium have absorption as well as emission bands in the red, and since the chief group of absorption bands of neodymium lies in the region between λ 5700 and λ 6300, it was very desirable to use a photographic plate sensitive to the yellow, orange, and red. Various makes of films and plates of American manufacture were tried, all of which except Cramer's Trichromatic were found to give very slight photographic action beyond λ 6100. Cramer's Trichromatic is fairly sensitive to between λ 6300 and λ 6400, but its photographic action is not very even, there being two well-marked minima in the visible spectrum.

The Wratten "Panchromatic," made by Wratten and Wainwright, of Croydon, England, was tried and found so satisfactory that it was used almost exclusively. A brief description of its properties from the standpoint of the worker in spectroscopy may not be out of place here, especially as red sensitive plates, which are at the same time sensitive to the rest of the spectrum, are not very plentiful.

The "Panchromatic" is very sensitive in the red as far as λ 7400, and in the ultra-violet at least as far as λ 2300, and it is almost uniformly sensitive throughout this region. A short exposure will reveal four faint minima at λ 4975, λ 5650, λ 6175, and λ 6675, the one at λ 5650 being much fainter than any of the others. With a full exposure it is very difficult to make out any of these minima, the action being apparently perfectly uniform. When the source is a Nernst filament the action in the red is a little more intense than that in the green or blue, while if the positive crater of the arc is used, the action is greatest in the bluish violet; this indicates a greater absolute sensibility in the bluish violet than in other parts of the spectrum, but the difference is less than in any other plate tried.

The plates are perhaps sensitive farther into the ultra-violet than λ 2300, for the spark used for comparison spectrum in the present work had no strong lines beyond this; so all that can be said is that they are about as sensitive at λ 2300 as the ordinary Eastman or Seed film. The plates must, of course, be developed in absolute darkness, for the light from the ordinary developing lantern fogs them as quickly as the light from a gas-jet fogs an ordinary plate. With this precaution and properly timing the development, there is no difficulty in getting good negatives, perfectly free from fog.

Glass plates could not be bent to the focal curve of the grating, and accordingly they were cut to such lengths (4 to 5 inches) that the definition would still be fairly good over the whole plate.

The region of the spectrum photographed was usually from about λ 3700 to λ 6700, and the dispersion in the first spectrum was such that this could be included on a plate 5 inches long. The plate-holder was movable in a direction parallel to the spectrum lines, and as the plates used were 2½ inches wide, several exposures could be made on one plate, which is indispensable when one is studying changes in the spectrum produced by variations in the conditions under which it is produced.

3. *Methods of observing the emission spectrum.*—In order to observe the emission bands of erbium oxide, all that is necessary is to dip a platinum wire in a fairly concentrated solution of the chloride or nitrate, and then hold it in the flame of a Bunsen burner. The oxide forms a more or less spongy coating over the end of the wire, and when viewed with a direct-vision spectroscope, the characteristic bands may be seen together with a considerable amount of continuous spectrum, part of which may be due to the white-hot platinum wire, but the greater portion in general to the oxide itself. The reason for this is that the spongy coating of oxide takes a very high temperature, and, as was found by Lecoq de Boisbaudran,[1] when the temperature rises the continuous spectrum increases in brilliancy much more rapidly than do the bands. In order, therefore, to see the bands to the best advantage, it is necessary to prevent the oxide from taking too high a temperature. This may be a done by making it more compact, by either one of the two following methods:

[1] *Loc. cit.*

a) Bend the end of a platinum wire into the form of a loop, put a small drop of a concentrated solution of the chloride or nitrate on it, and hold it in the flame. After a second or two the substance will be seen to blow out into the form of a tube generally from 2 to 4 mm in diameter and a centimeter or two long, closed at both ends. This tube is extremely thin and hence must be handled with some care to prevent breaking. It should be moistened with the solution and carefully heated again, the operation being repeated perhaps a dozen times, when it will be found that the walls of the tube have become quite thick and compact, or even that the tube has become a fairly compact solid rod, which will stand a considerable amount of rough usage. and which adheres firmly to the platinum wire. If its outer surface is very rough owing to the formation on it of very thin hollow projections, these should be removed; otherwise when the rod is heated, they will take a very high temperature, and hence give rise to the continuous spectrum which it is desired to avoid. Their presence can be readily detected, even when they do not form evident projections, by the fact that when heated they shine with a brilliant green light, quite unlike that of the rest of the rod, which is rather orange due to the bands in the red.

b) This method is based upon the fact that when the oxide of either erbium or neodymium in the form of a fine powder is moistened with a small amount of the chloride solution, it sets after a short time into a rather hard solid mass, a behavior very similar to that of "plaster of Paris" when moistened with water. If this mixture, before it sets, is put into a glass tube having an internal diameter of one or two millimeters, and then just as it is setting is pushed out by means of a close-fitting piston, very smooth, uniform rods of any desired lengths are obtained. A platinum wire may easily be fastened on to one of these rods by wrapping one or two turns of it around the end of the rod, and then covering it over with some of the freshly made mixture. Such a little rod, after having been carefully heated to redness, is generally rather brittle, but may be made quite tough and compact by being repeatedly moistened with the chloride solution and each time slowly heated to redness.

To observe the emission of erbium oxide when heated by cathode rays, vacuum tubes of the form shown in Fig. 1 were used. The

oxide was placed on a piece of platinum foil A which was situated at the focus of the concave cathode D. The side tube B was fitted to the main tube by means of a ground joint C, so that it was easy to take out the platinum foil A for the purpose of removing the coating of oxide. The wire F made it possible to connect the platinum foil to earth or to charge it to any desired potential.

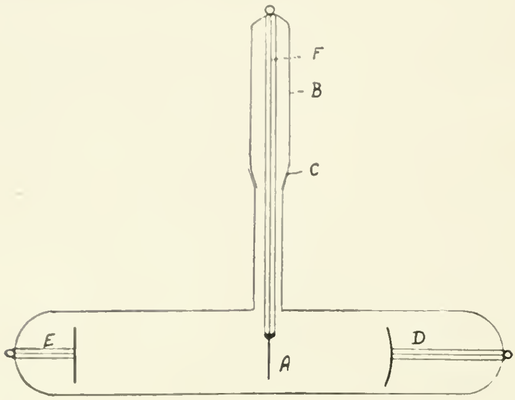

Fig. 1.

4. *Method of observing the absorption spectra.*—In order to observe the absorption spectrum of the solid salts it is necessary to focus some strong source of white light, such as the Nernst filament or the positive crater of the arc, on the dry powder, then throw an image of the spot of light on the slit of the spectroscope. For photographing the spectrum of the salts when these were at ordinary room temperatures, they were placed between two small plates of glass, held together with sealing wax; these were placed in such a position that their surfaces were parallel to the jaws of the slit. In order to avoid the light reflected from the glass surfaces, the light from the arc or Nernst filament was made to fall on the plates in such a direction that the angle of incidence was about 45°, in which case the reflected cone of light fell well off to one side. To examine the absorption spectrum when the salts or compounds were kept at temperatures above that of the room, they were spread out into a very thin layer on a piece of platinum foil, which was heated by a Bunsen burner. Various temperatures could be had by placing various thicknesses of sheet asbestos under the foil. This method was found to work satisfactorily up to temperatures of a dull-red heat. To observe or photograph the absorption spectrum at the temperature of the oxide when it is emitting, the arc was focused on the oxide while in the flame of the burner.

For observing the absorption of solutions a number of small cells were made out of a brass tube, the ends being covered by microscope cover glasses. In order to keep the solutions from attacking the brass all that was necessary, was to cover this with a thin coating of shellac.

OBSERVATIONS AND RESULTS

1. *Emission spectrum.*—*a*) Erbium oxide. The important question to decide in regard to the emission spectrum is whether the bright bands are in reality due to the solid oxide itself, or are to be ascribed to some surface layer of gas, formed by the action of the flame. The simplest and most direct way of settling this would be to heat the oxide without using a flame, for example by placing it on a strip of platinum foil and heating this by passing a current through it. This was tried but no definite results were obtained, because if a thin enough layer is used to allow it to take a temperature approaching that of the platinum strip, the radiation from the layer is so feeble that it is entirely masked by that of the metal, while if a thicker coating is used it does not get hot enough. In one experiment the oxide was highly heated in an electric furnace, but here the light from the porcelain tube of the furnace was overpowering, and besides, since the oxide was practically inside a hollow vessel whose temperature was nearly uniform throughout, nothing but black body radiation was to be expected. It was therefore decided to heat the oxide by cathode rays in a vacuum. This would certainly eliminate the chemical action of the flame, but would still leave the reducing action known to be a property of cathode rays. The method has, however, one great advantage over any flame, and that is that by controlling the vacuum and current-strength, the oxide may be heated to any desired temperature, from that of the room to the most intense white heat, and so is very well suited for the purpose of studying the change in the emission with temperature. As the oxide is heated gradually under the bombardment of cathode rays, the following may be observed:

At temperatures below red heat it gives out a greenish-yellow light, the so-called fluorescent spectrum, already studied and described by Crookes.[1] As the temperature rises the emission

[1] *Proc. R. S.*, **40**, 77–79, 1886.

bands in the green soon become visible, and almost simultaneously the bands in the red are seen. The bands in the red always have a considerable amount of continuous spectrum near them, while at low temperatures the bands in the green stand out from a relatively very dark background. With rising temperature the bands in the blue soon become prominent, and the continuous spectrum increases in intensity; simultaneously the bands become more and more hazy, and finally, when the temperature becomes very high, nothing is seen but a perfectly continuous spectrum. At this stage the oxide shines with a light as brilliant as that of a Nernst filament. These appearances were the same whether the platinum strip upon which the oxide was placed was connected to earth, or charged to a high positive potential by being connected to the anode. They were also the same when it was charged to such negative potentials as it was found possible to employ without disturbing the paths of the cathode particles too much. Usually when a negative potential of more than a hundred volts was employed, Wehnelt discharges of slowly moving cathode rays took place which seemed to come from isolated points of the heated oxide rather than from the whole surface. It is possible that the starting-points of these Wehnelt discharges were particles of such impurities as calcium, sodium, or potassium.

When one of these tubes had been used for a few hours, its walls near the strip covered with the oxide became coated with a black deposit. This was at first thought to be platinum, but was shown not to be that by the fact that it could not be dissolved by aqua regia, even when this was boiled in the tube. The only way found to remove the deposit was to scour it out mechanically by means of sand and water, although all the common acids were tried. The deposit was in all probability the metal of the oxides, these being reduced by the action of the cathode rays.

The emission of the oxide when heated in a cyanogen flame was also examined, and found to be identical with that observed when heated in a vacuum, by cathode rays, or when heated in a Bunsen flame. The object of using the cyanogen flame was to eliminate the reducing action of hydrogen.

b) Neodymium oxide. When neodymium oxide is heated in a Bunsen flame it gives a spectrum consisting of two extremely wide,

hazy bands, the intensity-curve of which is shown in Fig. 2. If, however, the oxide be present as an impurity in erbium oxide, it gives a fine series of bands in the yellow and orange, a photograph of which is shown in Fig. 3. It was also introduced as an impurity in calcium oxide, but the bands in this case were very much hazier; that is, the spectrum approached much more nearly that of the pure neodymium oxide.

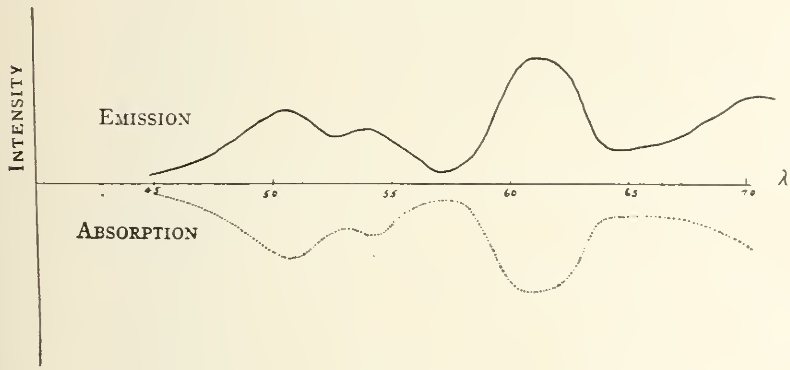

FIG. 2.

2. *Conductivity of erbium and neodymium oxides at high temperatures.*—According to a theory advocated by J. Stark, continuous spectra are due to the free electrons in a substance, and hence we should expect that unless a substance has an appreciable conductivity it should not radiate a continuous spectrum. At temperatures of 1200° C. or below, the continuous spectrum in the light emitted by a bead of erbium oxide is very faint, much more so than is the case with neodymium oxide. It was accordingly of some interest to get at least some relative values of the conductivities of these oxides at high temperatures.

The oxide was made into the form of a Nernst filament by the method already described above. The filaments actually used were about 15 mm long by 2 mm in diameter, and were very compact. This was ascertained by breaking each one after the measurements had been completed; the broken ends showed a very fine-grained structure like that of broken porcelain. They were heated by means of a small platinum furnace, the temperature of which was deter-

mined from resistance measurements made on the heating coil itself.

The conductivity of the filaments was determined by measuring the current through them when an E. M. F. of from 2 to 110 volts was applied; the current being measured by means of a d'Arsonval galvanometer (sensibility $= 2.3 \times 10^{-8}$ amperes).

The following are a few of the values found:

SPECIFIC RESISTANCE

Temperature	Neodymium Oxide	Erbium Oxide
1400 C.	1,860 ohms	20,000 ohms
1275 C.	4,000 "	100,000 "
1150 C.	7,500 "	200,000 "

No great accuracy is claimed for these values, the object being rather to find comparative values for the two oxides, than absolute values. They show, however, that at the temperatures given, erbium oxide is a very much poorer conductor than neodymium oxide, and if, as is very probable, the emission of a continuous spectrum is due to the presence of a large number of free electrons, this might suggest an explanation of the fact that neodymium oxide when present as an impurity in erbium oxide emits the bands much better than when by itself. The amount of neodymium oxide needed to give the bands to the best advantage is very small, perhaps less than one per cent., so this would not lower the resistance of the erbium oxide very much.

3. *Absorption by solid compounds.*—*a*) Erbium oxide. It was stated by Crookes[1] that if a bead of erbium oxide is illuminated with white light and examined with a spectroscope, a group of very fine lines is seen in the green, and he gives a diagram showing the positions of these lines.

Besides this group in the green, there is one in the red, one in the blue, and two in the violet, and also a number of fainter bands in various parts of the spectrum. The intensity of the absorption bands was found to vary considerably with the treatment previously given to the oxide. The three spectrograms reproduced in Plate VIII, Fig. 4, illustrate this. The first (*a*) is the result of an exposure to the light diffusely reflected from the oxide in the powder form, obtained by heating the oxalate; the oxide used in getting the second (*b*) was

[1] *Loc. cit.*

in the form of a rod which was made from the chloride solution by the first method described above. It had been heated in the Bunsen flame for at least one hundred hours before this spectrogram was taken. The third spectrum (*c*) was made by employing a rod made according to the second method described above, the rod having been heated in an oxyhydrogen flame for a length of time sufficient to make its surface appear as though it had begun to fuse. The great change in intensity may be explained by the following considerations:

In order that the light diffusely reflected from the solid salts may show absorption bands, it is, of course, necessary that it should have passed through some of the particles of the salt, that is, the light in which the absorption is observed is really transmitted light.

The intensity of the absorption bands will therefore be increased if the length of path traversed by the light in the substance is increased. Now, the fused oxide is probably fairly transparent, for when little rods of it are held in the electric arc for a moment, then withdrawn and allowed to cool, their surface presents a distinctly glassy appearance, which, when held in sunlight and viewed with a spectroscope, shows hundreds of very dark absorption lines or bands. The spectrum is identical with that shown in Fig. 4, *c*, only the bands are very much more intense, and hence a number that are too faint to be seen in the spectrogram, here show quite distinctly. Attempts were made to photograph the spectrum from these fused or glassy surfaces, but it was found so difficult to avoid streaks of continuous spectrum due to reflection from the surface itself, that it was given up.

Returning now to the spectra shown in Fig. 4; when the oxide is in the form of a very fine powder the length of path traversed by the light in the substance itself before it emerges, must be limited to the distance through a very few particles at most, and accordingly, as might be expected, only the strongest absorption bands would be seen. In the second case, where the oxide had been kept at a high temperature for a very long time, incipient fusion had undoubtedly taken place to some extent which would lengthen the path of light in the substance considerably. In the third case the fusion had progressed much farther, although the surface had not assumed the glassy appearance which it gets when the fusion is complete.

It was noticed that the chief groups of absorption bands agree approximately in position with the emission bands when the oxide is heated, and it was natural to assume that the absorption spectrum changes with temperature in such a manner as to become identical with the emission spectrum when high temperatures are reached. This was tried and found to be the case. Fig. 5 shows photographs of the emission spectrum (*a*), absorption spectrum of the oxide while in the flame (*b*), and absorption spectrum of the oxide at ordinary room temperatures (*c*). Visual observations showed that when the temperature is gradually raised the absorption bands became hazy and broaden out, finally running together into the broader bands corresponding to those of the emission spectrum. The individual bands are affected quite differently, as may be seen by noting the changes in the two principal groups in the green. The strongest band in the most refrangible group, as well as the band on its violet side, is shifted toward the red, while the chief band in the less refrangible group is not shifted at all.

The group of bands in the blue is also shifted toward the red somewhat, as is also the group at λ 3780 just beyond the cyanogen bands.

b) Neodymium oxide. The changes produced by change in temperature are also well marked in the case of the absorption of neodymium oxide. These are illustrated by the photograph reproduced in Fig. 6. The first spectrum in the figure shows the absorption of the bluish-gray oxide at a temperature somewhat below 100° C.; the second shows the same for a temperature of about 200°; the third for a temperature of about 400°, and the last one for a temperature of about 600° or a dull-red heat. None of the bands here shows any appreciable shift, but the changes in intensity are in some cases very striking. Consider the fine group of bands lying between λ 6200 and λ 5830. For convenience in speaking of them, they will be referred to by the letters *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, and *j*, beginning at the red. Near room temperature, *a*, *b*, and *c* are of nearly equal intensity, *c* being if anything slightly the more intense; *e* and *f* are of about equal intensity, so also *g* and *h*, while *j* is rather more intense than *h*. At 200° C., all the bands have widened somewhat, and the changes in intensity are about as follows: *c* has decreased very much, its intensity being

distinctly less than that of *a* and *b*, which are still equal; *d* has almost disappeared; the intensity of *f* is less than that of *e*, that of *h* very much less than that of *g;* while the intensity of *j* has decreased to less than one-half of its value at the lower temperature. A glance down the spectrum toward the violet shows that the group comprised between λ 4800 and λ 5500 has practically disappeared with a temperature-change of only a little more than 100° C. The bands at λ 4475 and λ 4427 have changed scarcely at all, while that at λ 4382 has had its intensity reduced to about half-value.

At 400°, the bands have widened still more. *a* and *b* are now the most prominent bands in the yellow group, with *b* slightly more intense than *a*, *c* is not specially conspicuous, while *d* can be seen only with difficulty; *e* is much more intense than *f;* *h* can no longer be distinguished, appearing now only as a slight shading on the violet edge of *g;* *j* is becoming very faint and hazy. The blue bands at λλ 4475, 4427, and 4382 have changed very little in intensity, but have broadened somewhat.

At 600°, *a* is rapidily losing its identity, while *b* is still fairly distinct; *c*, *d*, *e*, and *f* have run into one band with an intensity maximum corresponding with the position of *e*. The band due to *g* and *h* has become very hazy and faint, while *j* can be seen only with difficulty. The three blue bands are still fairly distinct.

At the temperature which the oxide takes when held in the flame of the Bunsen burner the absorption agrees exactly with the emission as shown by the dotted curve in Fig. 2.

When rods of neodymium oxine are heated in the arc, or in the oxyhydrogen flame, the surface fuses as in the case of erbium oxide. The fused surface is, however, almost jet black, indicating that fused neodymium oxide is much less transparent than that of erbium When sunlight is focused on the surface of this oxide, the bands may be seen, but they are so nearly drowned out by the admixture of white light reflected by the surface itself, that they are seen no better then when the fine powder is used. If the fused oxide could be made into very thin plates these would undoubedly be transparent enought to allow the absorption spectrum to be seen with increased intensity, since by this method the reflected light would be very nearly eliminated.

It is stated in chemistries[1] that the oxide of neodymium (Nd_2O_3), if not heated too strongly, is pinkish in color, while if heated to a bright red it turns to a bluish-gray color. Some of the pink oxide was examined and was found to give an absorption spectrum which is quite different from that given by the gray oxide. Fig. 7 shows the two spectra compared. By heating the pink oxide to a bright red it changes into the gray variety. An attempt was made to prepare this pink oxide from the oxalate by heating it very gradually in an electric furnace; but nothing could be obtained except the gray oxide. Similar results were obtained when starting with the chloride, nitrate, or sulphate; at more or less elevated temperatures they change into the gray oxide, and at no stage could even a trace of the bands of the pink oxide be found. It would be interesting to know whether the pink oxide really has the same formula (Nd_2O_3) as the other variety, and if so, what the molecular differences are which cause such a marked change in the absorption.

c) Other compounds. The spectra of a number of compounds of both neodymium and erbium were observed both visually and photographically. These compounds were the chloride, oxychlorides, nitrate, subnitrates, sulphate, oxalate, and acetate of neodymium, and the nitrate, oxalate, and sulphate of erbium.

Fig. 8 shows the spectra of the chloride, nitrate, sulphate, and oxalate of neodymium, the salts being all dry. These illustrate quite well the fact that the absorption is different for the different compounds. There is, however, a general resemblance among the spectra shown in Fig. 8 (Plate IX). The group of bands in the yellow, for example, although different in structure in the different compounds, still occupies about the same position, and if viewed in a spectroscope of low dispersion might easily be thought to be the same in the four compounds. The same holds for the double group in the green.

Even this general resemblance disappears in some of the other compounds. If the chloride is heated in air it first changes into an oxychloride, and this finally into the gray oxide. The spectra of these three are shown in Fig. 9. It will be seen that the group of bands in the yellow seems to move toward the red as we pass from the chloride to the oxychloride to the oxide. Similar changes may

[1] O. Dammer, *Handbuch der anorganischen Chemie*, Vol. IV, p. 648.

be noticed for some of the other groups. Such changes are also noticed when the nitrate is heated so as to change into the subnitrate, and these into the gray oxide. This apparent "motion" of a "group of bands" may perhaps be what Becquerel refers to in the quotation cited above. On closer examination, however, it becomes evident that we are not dealing with the motion of a group as a whole, for the arrangement of the bands in the displaced group is very different from those in the original.

It may be a little difficult to say just what is meant by saying that a group of bands moves as a whole. Motion implies a continuous change of position, such as we have, for example, in the temperature change in the absorption bands of erbium oxide. Here we have nothing of that kind, for what actually takes place is this: the molecules of $NdCl_3$, for example, are capable of absorbing certain wave-lengths, which may, to be sure, vary slightly with temperature; similarly, the molecules of the neodymium oxychloride which is formed when the chloride is heated in air, are capable of absorbing certain wave-lengths, which will in general be different from those absorbed by the chloride. If the spectrum is observed while the chemical change is taking place, both sets of bands are found to be present, those belonging to the chloride gradually decreasing in intensity, while those belonging to the oxychloride increase until, when the chemical change is complete, the chloride bands have entirely disappeared. Unless a group of bands in the oxychloride corresponds band for band with a similar group in the chloride spectrum, we cannot very well say that we are dealing with the same group, for it is probable that the individual bands in the two cases are due to different vibrators.

The narrow band near λ 4270 shown by aqueous solutions of neodymium salts is interesting in this connection. It appears in very nearly the same position in solutions of the sulphate, chloride, acetate, and nitrate. In the nitrate it is, however, double, and in the solution of the acetate it is wider than in solutions of the chloride or sulphate. In the dry salts a narrow band appears in about the same region, the wave-length being in general somewhat greater. In the oxalate, for example, there is a band at λ 4300; in the chloride there is also a strong band at about λ 4300, but there are besides three fainter bands near it, which are equally narrow, one of which falls at

about λ 4280. In the oxychloride referred to already there is no band near λ 4300, but there are four very narrow bands beginning at about λ 4370, and extending toward λ 4425. The pink oxide has a band at about λ 4310, while the gray oxide has no band before we get to the red side of λ 4375. In view of these facts we cannot be sure that the band λ 4270 seen in solutions is found shifted toward the red in all dry compounds, for we may be dealing with entirely different bands.

d) Crystals. As stated above, Becquerel found that the absorption spectrum of a crystal depends somewhat upon the direction in which the (polarized) light is passed through it. This was also observed in the case of neodymium nitrate crystals in this work. Light was passed first through a nicol and then through a flat plate of $Nd(NO_3)_3$ about 2 mm in thickness. In a given position of the nicol some bands were seen which entirely disappeared if the nicol was turned through 90°. The reason for this is of course that the crystals are doubly refracting and the absorption is different in the two rays. This was seen in a very striking manner in a small crystal of erbium chloride. The crystal was in the form of a small prism having a refracting angle of about 30°. When light was passed through this prism, the ordinary and extraordinary rays were separated very nearly as widely as they are in an Iceland spar prism of the same angle. The absorption in the two rays was seen to be quite different. Unfortunately the crystal melted before a determination of its optic axis could be made, but polariscopic observations on both chloride and nitrate of erbium and neodymium indicate that the double refraction of these substances is at least twice as great as in Iceland spar.

If the spectrum of a crystal is compared with that of the corresponding dry salt, we still find some differences, but they are very slight compared to those mentioned above. Fig. 10 shows the change in the absorption of erbium sulphate crystals when these are heated more and more: that is, when the water of crystallization is driven off. (The sulphates of both neodymium and erbium part with their water of crystallization without decomposition, by simply being heated in the open air.) The change illustrated in Fig. 10 is very similar to that due to temperature in the case of erbium oxide. The bands due to the crystals are wider than those of the dry salt, and are also

somewhat displaced toward the red. The displacement toward the red is also shown by neodymium sulphate, but the difference in width and general appearance of the bands is not very marked.

4. *Absorption of solutions.*—So much work has already been done on the absorption spectra of solutions of neodymium and erbium, that little attention was given to them in this work; it seemed, however, of some importance to compare the spectrum of a solution directly with that of the crystals obtained from it; and accordingly the spectra of solutions of the chloride, nitrate, sulphate, and acetate in various concentrations and those of the corresponding crystals were photographed to the same scale so that comparisons could be made with ease. Fig. 11 shows the absorption of an aqueous solution of the sulphate of neodymium in concentrations varying from $\frac{1}{8}$ normal to $\frac{1}{64}$ normal, compared with the absorption of the crystals deposited from the stock solution of sulphate. The general resemblance between the spectra is very apparent, but there are, however, differences especially well marked in the group in the yellow. In the crystals this group is seen broken up into individual bands, while in the more concentrated solutions, although the width of the group is smaller, the bands are not separated. In the $\frac{1}{32}$ normal solution the yellow group is seen broken up into four or five bands, whose positions are, however, different from the bands seen in the spectrum of the crystal. A $\frac{1}{16}$ normal solution of either the chloride or the nitrate shows the group broken up exactly as it is in the sulphate solution, although, as we have seen above, the bands in this group, in case of the crystals of the nitrate and chloride, are quite different.

Speaking very generally, it may be said that the spectra of solutions of different salts are nearly alike, while the spectra of the dry salts are very different. The spectra of the crystals seem to be, as it were, intermediate, differing from the two extremes much less than the extremes differ from each other.

DISCUSSION OF RESULTS

It has been shown that the absorption of the solid oxide at high temperatures corresponds exactly to the emission at the same temperature in accordance with Kirchhoff's law. This shows that the emission and absorption of the oxides, and presumably also of the

phosphates, are really both due to the same vibrators. The absorption of the oxide is very similar to that of other solid compounds, so that it is reasonable to suppose that the mechanism of the absorption spectrum of all solid compounds is the same. The general resemblance between the spectrum of a dry salt, the crystals, and the corresponding aqueous solution indicates that these are also due to the same thing. It seems reasonable therefore to assume that the three kinds of spectra defined above are due to the same vibrators, and there remains only to find the causes which produce the variations which are observed.

Let us assume that the vibrators in question are electrons located inside the metallic atom; these electrons are held in positions of equilibrium by forces due partly to the positive charge of the atom itself and partly to the other electrons inside it. It is evident that an atom consisting of a region positively charged and having in it a number of electrons whose combined charge is sufficient to neutralize the positive charge, although neutral for a point far away from its center, will still exert forces on charged bodies near it; or, we may say, the electric field of a Saturnian atom vanishes for points far removed from the atom, but not for points in its immediate neighborhood. It is also evident that the field in the immediate neighborhood will be different for atoms of different substances.

Now, to fix ideas, let us consider a neodymium atom having inside it certain electrons which may be set in vibration by light-waves falling upon them. If an atom of another substance such as chlorine is brought very near to it, the electric field of the chlorine atom will affect the periods of these electrons. It is also to be expected that an oxygen atom will produce a different change in the period, since its electric field is undoubtedly different from that of the chlorine atom. This indicates why the different compounds should show different absorption spectra.

To explain the temperature change, which, as we have seen, consists chiefly of a widening of the bands, we have only to consider that the periods of the vibrators will be a function of the distance between the disturbing atom and the atom containing the electron. If this distance is continually varying, that is, if the two atoms are vibrating with reference to each other, the period of the electron will also be

changing; in other words, the absorption it occasions will be a band rather than a line. Now, with increasing temperature the oscillations of the atoms in a molecule have their amplitudes increased and hence we should expect the bands to widen.

That the presence of water of crystallization should produce a change similar to that of raising the temperature indicates that the presence of water molecules diminishes the forces holding together the atoms forming the molecule, thus increasing the amplitudes of the oscillations; this is also what might be expected when it is considered that water has great dissociating powers, which depend primarily upon diminishing the forces holding the parts of a molecule together.

The fact that the spectra of aqueous solutions of different salts of the same element are so nearly alike may be due partly to the fact that the salts are dissociated, and hence the metallic ion is surrounded by water molecules, and hence would be in almost the same condition, no matter what salt is dissolved. It is also probable that even if the molecule of the dissolved salt is not dissociated, the effect of the molecules of the solvent in modifying the periods of the vibrating electrons would be very great.

SUMMARY

The results may be summed up in the following statements:

1. The bright band emission spectra of the oxides of erbium and neodymium are due to the oxides themselves, and correspond exactly to their absorption at the same temperature.

2. The absorption of the solid compounds changes with temperature, the change consisting in a widening of the bands, and in some cases a shift toward the red, as the temperature is increased.

3. The absorption spectra of dry compounds are different for different compounds of the same element.

4. The presence of water of crystallization in a compound seems to change its absorption in the same way that a rise in temperature does.

5. The results are satisfactorily accounted for by assuming that the vibrator responsible for the spectra is the electron inside the metal-

lic atom, its period of vibration being affected by the presence of other atoms or molecules.

In conclusion I wish to thank Professor Ames, who suggested the work, and under whose direction it was carried out, for his unfailing interest and many valuable suggestions.

Johns Hopkins University
June 1907

PHYSICAL NATURE OF METEOR TRAINS

By C. C. TROWBRIDGE

Meteor trains are luminous clouds formed by meteors which persist long after the incandescent nucleus has disappeared. They not infrequently remain visible to the naked eye for many minutes, and in a number of well-authenticated instances have been observed to last even as long as three-quarters of an hour. From a study of many recorded observations it is evident that meteor trains seen at night are self-luminous, and are sometimes bright enough to be seen several hundred miles distant. The trains vary from ten to even thirty miles in length when first deposited and rapidly expand in width, and those that are visible for over ten minutes are usually found to be a mile or more in diameter.

Previous investigations on the subject.—Meteor trains, or "persistent streaks," as they are often called, have been observed by many astronomers, but the cause of their luminosity is still regarded as an unsolved mystery. Only a few papers have been published which deal directly with the subject, but there are many which contain careful records of observations of trains incidentally seen by meteor observers while engaged in mapping radiant points and in the study of other problems of meteoric astronomy.

J. Ennis has described seven different trains[1] seen by various persons, and E. E. Barnard has published a paper on the drifts of five trains observed by him at Nashville, Tenn.,[2] in which also he calls attention to the importance of the phenomenon. While in a few other papers the subject has been referred to in a general way, no systematic attempts to collect the records together appear to have been made hitherto. It is the belief of the writer that valuable facts concerning the earth's atmosphere can be obtained from a study of the records which already exist. With this end in view a catalogue of meteor trains has been compiled and the records made the subject of a comparative study for several years. At the same time the writer has made a study of gas phosphorescence in the laboratory.

[1] *Proceedings of the American Association for the Advancement of Science*, 1871.

[2] *The Sidereal Messenger*, 1, 174, 1883; 10, 426, 1891.

The reliability of the records.—The observations of meteor trains have been made chiefly by well-known astronomers at astronomical observatories, or by trained meteor observers, who have recorded the facts in scientific journals. Most of the observations have been made since 1800. They are complete in many cases; while in others only a few details are given. The greater part are trustworthy and scientific records. Among the astronomers who have made observations are the following: In England: Denning, Herschel, Corder, Greg, Backhouse, Booth, etc.; In the United States: Twining, Newton, Kirkwood, Young, Barnard, Gilman, etc.; In other countries: Schmidt, von Niessl, von Konkoly, Schiaparelli, etc. A systematic study of these records is a work of no little magnitude. The observations which have formed the basis of the writer's comparative study of the trains are chiefly those made in England and the United States, but it is intended to take up later all records that can be found, including those in other countries. The facts given in this paper are therefore only a portion of the available records, and are necessarily of the nature of a preliminary report, but they are of sufficient interest to warrant their presentation at this time. About 175 observations have been studied of trains having a duration which positively identified them with the phenomenon under discussion. The subject is treated under the following heads:

1. Altitude of meteor trains.
2. Color of meteor trains.
3. Visible duration of meteor trains.
4. Explanation of the meteoric glow or "auroral light."
5. Probable explanation of the dual appearance of trains.
6. Diffusion of meteor trains.
7. Drift of the atmosphere at great altitudes.
8. Resemblance of the meteor train to the afterglow produced by the electrodeless ring discharge.
9. Summary of the chief results obtained.

I. ALTITUDE OF METEOR TRAINS

The determination of the height at which meteor trains occur is important, not only in establishing the altitudes of atmospheric currents shown by the drift of the trains, but also because it may throw

light on the physical cause of the phenomenon. It is the purpose of the writer to show that meteor trains that are observed at night occur at a very definite altitude, and furthermore that there are various facts which indicate that the formation of the train is due rather to the state of the earth's atmosphere where the train is formed than to the constitution, size, or condition of the meteor itself.

The observations on the altitude of meteor trains have been very accurately made in a few cases and approximately made in a number

TABLE I

ALTITUDE OF THIRTEEN METEOR TRAINS OBSERVED FROM TWO OR MORE STATIONS MANY MILES APART

Catalogue Number	Altitude Limits of Visible Track of Nucleus—Miles		Altitude Limits of Train—Miles		Mean Altitude of Train—Miles	Altitude Computation Made by
	Beginning	Ending	Beginning	Ending		
10					50	A. S. Herschel
12	100	53	59	53	56	A. and J. Thompson
26					54	A. S. Herschel
29[1]	120	60	65	60	63	H. A. Newton
44	68	49	59	49	54	H. A. Newton
46					51	H. A. Newton
47	65	52			58	H. A. Newton
52[2]					59	H. A. Newton
80	90	30	58	50	54	W. F. Denning
120	78	47	59	47	53	W. F. Denning
121	65	37	57	45	51	W. F. Denning
125[3]	65	28			45	W. F. Denning
129	90	41			54	A. S. Herschel and Greg
Mean	82.8	44.1	59.5	50.7	54.0 miles =87.0 km.	

[1] "Over sixty miles"—train five miles long, carefully calculated.
[2] Altitude of lower part of train.
[3] Short train ½° long at forty-five miles.

of others. Table I contains the heights of thirteen trains seen at night, which were observed from two or more stations widely apart. In some cases ten or fifteen simultaneous observations were made. The table gives the altitude of the trains above the surface of the earth in miles. The average of the heights above the surface of the earth of the middle portion of the trains is 54.0 miles or 87.0 kilometers. In a previous paper by the writer[1] among the altitudes for meteor trains given were several greater heights than any of those in Table I, but these have now been discarded because, on studying the

[1] "Abstract," *Physical Review*, 24, 514, June 1907

original records, it was found that the figures given referred to the meteor track and not the train.

The position of eight meteor tracks with their accompanying trains with respect to the earth is shown in a chart, Fig. 1. They are drawn approximately to scale for length of path, altitude of train,

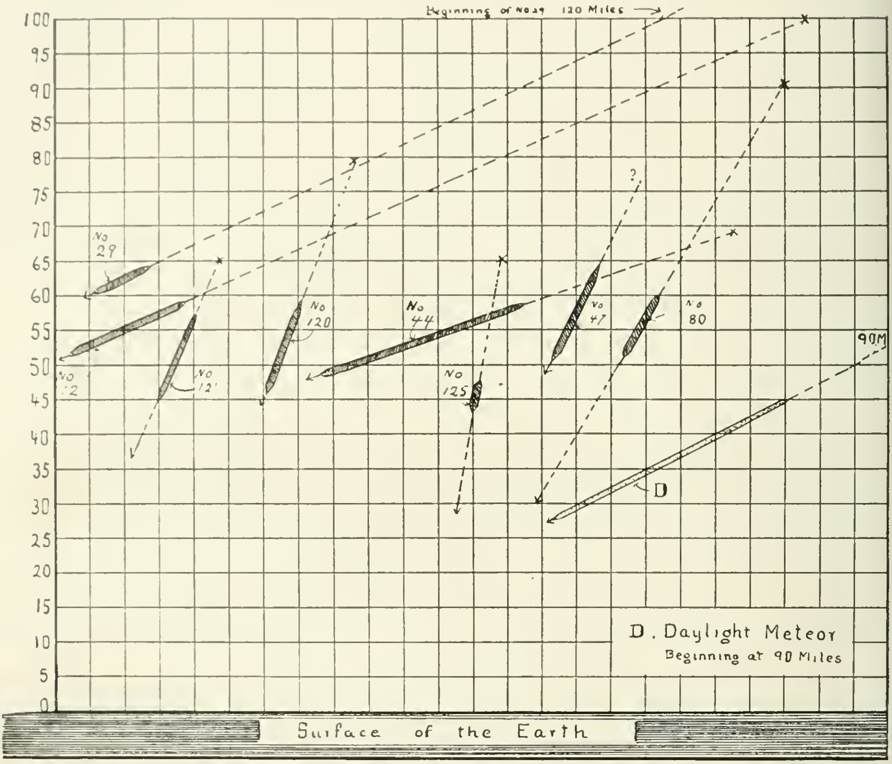

FIG 1 —Chart Giving the Altitude of Eight Self-luminous Meteor Trains and the Corresponding Lengths of Meteor Tracks.

and as near as possible angle of flight to accord with the recorded length of train. In all cases the meteors were observed at two or more stations and the heights, etc. were calculated by either W. F. Denning or H. A. Newton, except in one case.

No. 29, Yale Observatory, New Haven, Connecticut, November 14, 1866, 2:11 A. M. (many observations). Altitude of track, 120 to 60 miles; "train over sixty;" visible nine minutes; calculations by H. A. Newton.

No. 44, Yale Observatory, New Haven, Connecticut, and many other observatories, November 14, 1868, 1:12 A. M. Train extended from 59 to 49 miles altitude, and was 30 miles long at first; remained visible 44 minutes; calculations by H. A. Newton.

No. 80, observed in central England, August 26, 1894, 10:20 P. M. D. E. Parker and others; calculations by Denning; 90 to 30 miles; length of path, 66 miles; train 8 miles long, center being at 54 miles altitude; visible for 30 minutes.

No. 120, Leeds and Bristol, England, August 13, 1888, 11:33 P. M., observed by Denning and others. First appearance at 78 miles; extinction at 47 miles; train extended 18 miles from 59 to 47 miles altitude.

No. 121, Bristol and Sunderland, Eng., November 14, 1888, 5:19 A. M.; F. W. Backhouse and Denning. The meteor appeared at 65 miles altitude and disappeared at 37 miles over the North Sea. The train extended from 57 to 45 miles.

No. 12, Cardiff and Sidmouth, England, November 14, 1866, 1:08 A. M. At beginning 100, at ending 53 miles; length of streak, 16 to 18 miles at the lower end of the meteor's track.

No. 47, Eastern United States, November 14, 1866, 2:48 A. M. See Fig. 4.

No. 125, Bristol and Stonyhurst College, England, December 4, 9:17 P. M. A short streak at 45 miles altitude; calculations by Denning.

It appears probable from the chart, Fig. 1, that the altitude above the earth at which the persistent train is formed does not depend on the height at which the nucleus begins to glow. Interesting cases in favor of this point are meteors Nos. 12 and 29, which traveled forty or fifty miles as bright incandescent nuclei before the train zone was reached where trains were deposited. The nuclei of Nos. 44 and 80 traveled over twenty-five miles before the point was reached where the trains were formed. In the report of the Luminous Meteor Committee of the British Association for the Advancement of Science, 1867 (p. 405), among the records of observations of the shower of November 14, 1866, from different stations are the following accounts showing that the meteor trains in general were deposited only along a portion of the meteor track. Mr. Greg, reporting from Manchester and referring to the meteors and train, stated that "in the case of the larger ones with disks of 2′ or upwards the nucleus seemed finally to emerge from, or to shake off, or lose the phosphorescence for the space of a few degrees and then vanish." Mr. Glover, reporting from Chesham, stated "in nearly every instance the head ceased to emit a train before it vanished." Also Mr. Goulier at Metz reported that "a remarkable peculiarity of the meteors was that the streaks

were shorter than the entire length of their course, the nucleus shooting ahead of the train for some space without emitting the phosphorescent light of the streak."

From the foregoing facts it is evident that trains seldom if ever occur below 45 miles altitude or over 65, the usual height being between 50 and 60 miles (80 to 100 km), which agrees with a statement previously made by W. F. Denning. In this zone 50 to 60 miles above the surface of the earth there seem to be conditions which are favorable to both the formation and the persistence of the mysterious luminosity of the meteor trains. The condition of a gas which is most important in the production of electrical discharges, and in the formation glows is gas pressure. It is very probable, therefore, that the pressure of the atmosphere prevailing from 45 to 65 miles of altitude is such that self-luminous trains can be formed and be visible between those heights only. Fifty-four miles (87 kilometers) appears to be the altitude which is most favorable for longest visible duration.

II. COLOR OF METEOR TRAINS

The colors of meteor trains show a good deal of variation according to the published observations. Among the colors recorded are red, orange yellow, yellow, emerald green, blue, silver, and also white. In the accompanying tables the trains seen in darkness are separated from those shining by the reflected light of the sun and the two sets show a marked difference. The observations used in the tables are only those where very definite statements were made, and those of trains which persisted with a few exceptions longer than a minute. This eliminated the possibility of confusion of the color of the train proper with that of the nucleus, or with that of the mass of sparks which sometimes persists for a few seconds in the track of a meteor.

Among the trains observed at night, in Table II, in several cases green trains changed gradually to white, and in one instance from greenish to a "dull reddish or warm color." Out of the twenty-seven self-luminous trains, twelve were of various shades of green, and eleven either bluish, silver, or white. If, as in several cases observed, the trains change from green to white, a number of white-appearing trains are to be expected in the case of green trains of a low degree of luminosity. Many of the trains in Table II were those formed by

Leonid meteors, the trains of which are usually green, while those left by the Perseid meteors are more likely to be yellowish. The self-luminous meteor train of long duration therefore appears to be a light of fairly consistent hue. If the phenomenon is a gas phosphorescence a slight change in the constitution of gas in the train would no doubt alter the color somewhat, for the color of gas phosphorescence has been found by H. F. Newall to vary for different combinations of gases.[1] Train No. 26 in Table II was reported

TABLE II

COLOR OF METEOR TRAINS OBSERVED AT NIGHT (SELF-LUMINOUS)

The Author's Catalogue Numbers	Color	Number of Trains
19, 125	Orange	2
26	Yellow	1
15, 21, 28, 32, 41, 42, 45, 80, 85, 87, 88, 95	Green, emerald green, or bluish green.	12
12, 43, 44	Blue (also greenish blue)	3
13, 27, 39, 62	Silver or grey	4
10, 117, 123	White	3
71 (changed from)	"*Red* to bluish"[1]	1
89 (changed from)	"Greenish to dull reddish,[1] or warm color."	1
Total		27

[1] Red probably refers to track of sparks.

in a catalogue of meteors as having an orange-red train, but according to the original paper the correct record is "a pale-yellow cloud." Red was not mentioned.

The eleven trains in Table III were in sunlight. Most of these

TABLE III

COLOR OF METEOR TRAINS (ILLUMINATED BY SUNLIGHT)

The Author's Catalogue Numbers	Color	Number of Trains
74, 116	Red	2
70, 82, 111	Pink	3
3, 31, 93	White	3
40 (11:40 A. M.)	Light blue	1
4 (5:26 P. M.)	White turning to red	1
5 (2 P. M.)	Yellow turning to red	1
Total		11

[1] *Proceed. Cam. Phil. Soc.* **9**, 295, 1898.

were seen soon after sunset and illuminated by the sun, owing to their great height. Seven of these trains can be classed as red, and all the colors observed might be expected in case of illumination by the sun. A number of other daylight trains not given here show the same characteristic colors.

III. VISIBLE DURATION OF METEOR TRAINS

The time that a meteor train seen at night remains visible depends on the initial intensity of the train, the state of the atmosphere, the altitude of the train above the horizon, the distance between the train and the observer, and also on the keenness of the attention of the observer. Some idea, however, of the average duration can be had from the following reported observations. In a list of meteor trains collected, 53 trains having a duration of more than one minute were as follows:

6 remained visible over 40 (40–60) minutes
7 remained visible over 20 (20–40) minutes
12 remained visible over 10 (10–20) minutes
12 remained visible over 5 (5–10) minutes

There were therefore 37 trains which remained visible to the naked eye from five minutes to one hour, the average of 53 trains being 14.8 minutes.

Thus it is seen that many meteor trains persist for ten or twenty minutes after first appearance. In the opinion of the writer, the phenomenon is a gas phosphorescence; first, because of the rapid lateral expansion of the train, evidently a gas diffusion amounting to a mean rate of over 100 meters per minute; second, because of the great volume contained within the boundary of the train, usually being a matter of several cubic miles; and third, since the observed spectrum appears to consist of a few bright lines.

Whatever may be the exact nature of the excitation of the phosphorescent light of meteor trains, the rate of decay of the glow seems likely to correspond to the rates found by laboratory experiment. Nichols and Merritt have established the fact that in the case of phosphorescent solids, such as zinc sulphide, the luminescence decays according to the formula $I=\frac{1}{(a+bt)^2}$, an expression first suggested by Becquerel[1] in 1891.

[1] *Physical Review*, 22, 279, 1906

Recently the writer has shown by experiments on the afterglow formed in air at low gas pressures by the electrodeless ring discharge, that the rate of decay of luminosity of a phosphorescing gas is expressed by the same law exactly. The curves, shown in Fig. 2, are specimen decay curves of this gas phosphorescence, and the straight lines in Fig. 2 were obtained by plotting $I^{-\frac{1}{2}}$ instead of I, $\frac{1}{2}I^{-\frac{1}{2}}$ instead of $\frac{1}{2}I$, etc. From the formula it is possible to compute

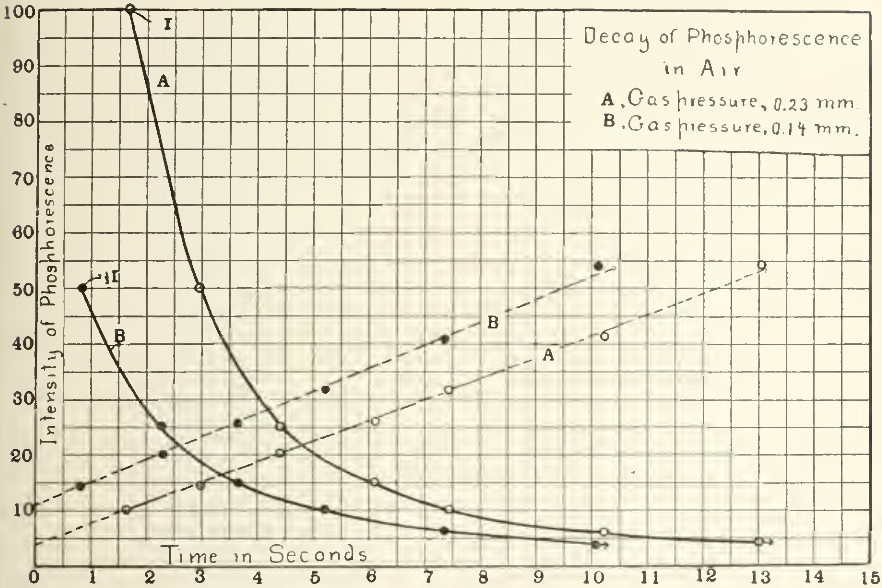

FIG 2.—Curves Showing the Decay of Phosphorescence in Air at Two Different Gas Pressures

the value of intensity of the glow, after it has been fading for 10 or 20 minutes. The value found for the intensity can be considered to be approximate, even if the law does not hold exactly for long-time phosphorescence.

The intensity at the end of 20 minutes is found to be $\frac{1}{250000}I$ (I = standard luminosity used in experiments), a value so small as not to be visible in a discharge tube of 4 centimeters diameter. The limit of visibility of the phosphorescence in a tube of these dimensions seems to be about $\frac{1}{7000}$ I. If the meteor train is considered to be a gas phosphorescence of the same nature as the afterglow and is one

mile in thickness, then the total effective luminosity would be of the order of 20,000 times the brightness of the afterglow in the discharge vessel, making no allowance for distance, the intrinsic brightness being about the same intensity, or $\frac{20000}{250000} I$. This value, about $\frac{1}{12} I$, is equivalent to the intensity of the light which is reflected from a slightly tinted screen of paper placed about 2.35 meters from an electric lamp of 6.5 candle power, an intensity of illumination which would seem to be amply great enough to appear bright in the sky. This calculation is only meant to show that the order of brightness of a phosphorescent gas, even after it faded for twenty minutes, is great enough for visibility provided there is a thick enough layer of radiating matter. If the meteor train is a gas phosphorescence, its long visible duration would appear to be readily explained. Moreover, the rate of decay for the afterglow has been found to be very much slower at lower pressures than the rates in the examples given, and also slower at higher pressures under certain conditions. In fact, on one occasion the gas was visibly phosphorescent, although very faint, 19 minutes after an excitation. The decay curves shown in Fig. 2 were obtained with a special photometer devised for the purpose by the writer. These curves were each formed by one decay of the afterglow only and show the smallness of the experimental error. No work on the decay of gas phosphorescence appears to have been done previous to this.

IV. EXPLANATION OF THE METEORIC GLOW OR "AURORAL LIGHT"

A curious brightening of the sky has been noted during meteoric showers around the region of the radiant point of the meteors. Professor Challis (Cambridge, Eng.), in reporting his observations on the Leonid shower of November 13, 1866,[1] made the following statement, which is perhaps the best record of the phenomenon:

> During a great part of the time over which the observations extended, there was a kind of glow throughout the heavens, a phenomenon which I was familiar with by my previous experience at the Cambridge observatory, and which my assistants also noticed and were accustomed to call "auroral light." It was however never accompanied by auroral streamers. Mr. Glaisher has informed me that the magnets at Greenwich were remarkably quiet during the night of November 13, 1866.

[1] *Monthly Notices*, 27, 75, 1867.

The explanation of the phenomenon would appear to be as follows: During the shower mentioned fully 2,000 meteors per hour were recorded as shooting from the radiant of *Leo*, in fact many observers reporting over 100 per minute. While a small percentage of these meteors produced visible trains, each meteor must have produced a train of phosphorescent matter of a certain degree of luminosity; also at any one time all the trains were in different stages of decay of luminosity, but *all* were giving forth some radiation. Several thousand feebly luminous trains were thus diffusing through the atmosphere around the radiant point of the shower. The trains were of course invisible individually, but in the aggregate were probably sufficiently luminous to make a pale light in the region of the sky through which the meteors had passed. If the meteor train is the same as the gaseous [illegible] which can be produced in the laboratory, then a phenomenon precisely similar to the described "auroral light" would be expected in every great meteor shower.

V. PROBABLE EXPLANATION OF THE DUAL APPEARANCE OF TRAINS

Many meteor trains appear double, as if formed by a double nucleus. This explanation of their double appearance was held by H. A. Newton, of Yale University, who, in reporting the observations of Gilman, November 1868, made at the Palisades Observatory, N. Y., states his opinion thus: "I think the double train of this meteor and other meteors is due to the actual duality of the meteor itself." Three drawings of double trains are reproduced in this paper from illustrations accompanying Newton's paper[1] describing the Leonid shower of 1868. This question is of importance, for while it is to be expected that in very rare cases the meteor would break in two, becoming two nuclei, and form a double train, from a study of many other trains by the writer the double appearance of the trains appears to be due rather to a greater luminosity on the border of the train than to a double train formed by two nuclei. The double train is then explained on the hypothesis that the train gradually becomes a tube of luminous matter which, viewed from the side, appears like a double line of

[1] *American Journal of Science and Arts*, 47, 399, 1869, and Plates.

light. The effect may be caused either by the dying-out of the luminosity along the axis of the train, or a greater luminosity at the border.

FIG 3.—Train Appearing Double as Seen in the Telescope.

Some of these double trains are shown by

Figs. 3, 4, and 5, which were originally drawn by W. S. Gilman, Jr., of the Palisades Observatory, N. Y., where the trains were observed.

Fig. 3 shows train of a meteor which appeared at 1:53 A. M., Nov. 14, 1868, in a 4-inch telescope, magnifying power 40.

Fig. 4 is another train as seen by telescope which appeared at 2:48 A. M. on the same evening and is referred to by Gilman thus: "The train was double (*as often observed during the evening*) and terminated in an oval cloud at right angles to the direction of the meteor's flight."

Fig. 5 shows a train which appeared at 11:25 P. M. also on the same night, Nov. 3, as seen by the naked eye. "In the telescope, power 40, diameter of field 43′, it presented a double line of bluish-green luminous matter."

FIG. 4.—Train Appearing Double as Seen in the Telescope.

It is evident from the foregoing that many meteor trains which would appear to the naked eye like a single bar of luminous matter might exhibit a dual appearance if observed through a small telescope.

A number of descriptions of meteor trains seen at night also substantiate the writer's view in regard to the greater luminosity on the border of the train. Thus, No. 53 of the writer's catalogue, November 14, 1868, 2:33 A. M., Madrid, Spain, is described thus: "A large fireball in *Ursa Major* left a train visible ten minutes which expanded 6°–8° in width, then faded out in the center so as to form a ring." Also No. 82, a very wonderful train seen at midnight at Grahamstown, South Africa, October 22, 1895, and carefully reported: "The train was 30° long, and widened out to one degee at one end and three-quarters of a degree at the other. The edges of the train were brighter than the center," etc.; visible 30 minutes. Professor E. E. Barnard observed a train in November 1901, which gradually expanded so as to appear "like a comet with a double tail." A drawing of this train was sent to the writer by the observer, showing the changes in the shape of the train. An observation of a long bright double train was made by W. Shackleton, on October 12, 1904, 11:39 P. M., London.[1] A portion of the report is as follows: "The train was tubular or consisted of two parallel narrow ribbons, each component being about twice the angular diameter of *Jupiter*, or about 90″ in width, separated by an interval of 5″." The train was observed in a telescope and remained visible for nearly twenty minutes. There are other good drawings and records of double night trains not mentioned above. Barnard mentions two trains brightest in the center,[2] as follows:

FIG. 5.—Train as Seen by the Naked Eye, Which Appeared Double in the Telescope.

Train No. 112, August 5, 1882, 9 P. M.: "It appeared at first very bright and unbroken, straight as a shaft, clean and sharp in

[1] *Monthly Notices, R. A. S.*, **66**, 89, 1904.

[2] *Sidereal Messenger*, **10**, 426, 1891.

outline, and brighter along the axis, but in *two seconds*, it became crooked and sinuous, etc." Also train No. 113, August 12, 1882, 3 A. M.: "watched in the telescope for nearly *five seconds*, in which it appeared long and perfectly straight, much brighter along the axis."

These observations tend to confirm rather than to refute the theory of the tube-like distribution of the luminosity of the train, since if the rate of the decay of the phosphorescence is more rapid, directly in the meteor track, the light would be at first bright and then faintest along the axis of the train. The bright axis was observed in the two cases mentioned above apparently only immediately after the train was formed. In all cases of "double trains" described, the

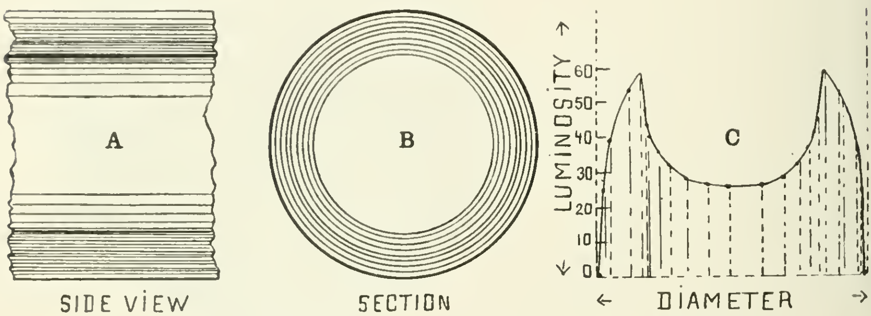

FIG. 6.—Graphical Explanation of the Dual Appearance of Meteor Trains.

observations were made at least one minute after the formation of the trains.

In Fig. 6, *A* shows a side view of a tube of luminosity such as is supposed in the case of a meteor train. *B* shows the tube in cross-section, end on, and *C* gives the variation of luminosity of a tube of luminosity such as *B* as seen from the side. The luminosity near the outside is twice as great as that in the center, although of course the luminosity of the meteor train would not be so uniformly tube-like. If the luminosity was distributed throughout a cylinder, the train as viewed from the side would appear brightest in the center; but as has been shown the reverse appears to be the case. Records indicate that trains obscure stars but little over which they pass, hence the absorption factor cannot be very great. In this connection it is important to note that gaseous glows are brighter with increased

thickness of the glowing volume, as shown in the case of the "after-glow" in the laboratory, and also that observation has been made to the effect that meteor trains observed end on, or those formed by meteors falling directly toward the observer from the radiant, are usually brighter than those seen from the side.[1]

Double appearance of daylight meteor trains.—A few trains shining by the reflected light of the sun show double lines of cloud. A meteor train as seen in twilight from Paris, June 11, 1867, 8 P. M., is shown in Figs. 7, *A* and *B*. The drawings are copied from those made by M. L. Roussy, chromometer-maker of the Toulouse Observatory.[2] In Fig. 7, *A*, the train is shown as it appeared 8 minutes after the passage of the meteor; in *B*, as it appeared about one hour later at 9 P. M., and described by the observer as follows: "The point *a*, formed by the apex of the triangle where two lines of the streak *ab*, *ac*, met together without any portion of the streak between them." This observation shows the gradual formation of a double train out of one which was single at first. In this case the train was probably shining in sunlight; hence the double track in this case may have been an increase of cloud density near the outside of the train, not unlikely a condensation phenomenon. Two different drawings by other observers also show duality of the same train.

Two other trains both seen in twilight in eastern United States, August 24, 1869, trains Nos. 55 and 56 of the writer's catalogue, were reported as expanding into double trains, but only the latter appears to be a double train as shown by the observer's drawings. The ring effect which appears in the picture of No. 55 was undoubtedly produced by perspective.

There is thus seen to be not a little data to substantiate the view that the trains gradually become tube-like.

Further facts are required for a definite conclusion in this matter. It is an important feature of the investigation, however, since under some conditions phosphorescent glows in gases appear to decay more rapidly in the immediate region where they are formed. The double train of daylight meteors observed may possibly be due to an acci-

[1] Wood, *Report of British Association for the Advancement of Science*, 1867, p. 83 (L. M. Com.).

[2] *Ibid.*, p. 380.

dental formation, since the only records of double daylight trains yet found by the writer are No. 31, shown in Fig. 7, and No. 56, mentioned above.

VI. DIFFUSION OF METEOR TRAINS

Almost all descriptions of meteor trains agree that there is a gradual enlargement of the phosphorescent streak. The change is usually referred to as the "expansion of the train." In many cases the extent of this expansion has been noted at several intervals of time after the formation of the train. The phenomenon seemed to be clearly a case of gas diffusion. This is shown by a comparison of numerous records. That the matter is a highly important one needs no argument, because it is evident that if accurate observations are made of this diffusion in the future and the observations made in the past are thoroughly studied, it is likely the pressure of the atmosphere at an altitude of 50 and 60 miles can be determined with approximation. This portion of the study of meteor trains is a long research in itself; therefore no definite conclusion can be arrived at now concerning the pressure of the atmosphere in the meteor train zone. In several cases the dimensions of the trains have been found in the records, and from these the mean rate of diffusion has been determined. These values are given in Table IV together with three trains carefully observed, but where the altitude above the earth has been assumed by the writer to be 60 miles and the rate of diffusion calculated on that basis. In these cases it was necessary to find the distance of the train from the observer by the use of star globe and some simple computations.

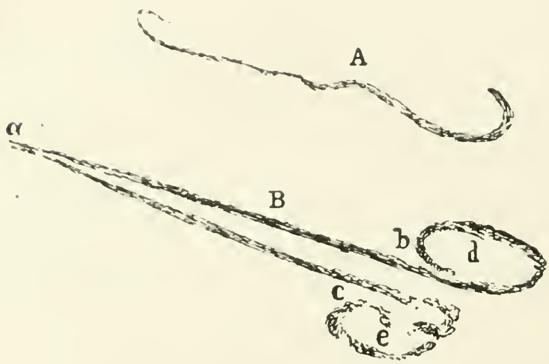

FIG. 7.—Train of a Twilight Fireball Showing Cloud Appearing Double.

TABLE IV
DIFFUSION OF METEOR TRAINS

No.	Width of Train —Miles or Degrees	Time Expanding —Minutes	Mean Velocity, Meters per Minute	Mean Diffusion Rate, Meters per Second	Height of Train—Miles
12	1 mile	10	80.5	1.3	56
29	3 miles	9	274.0	4.5	60
80	4 miles	17	189.0	3.1	54
87[1]	$1\frac{1}{2}°$	16	95.0	1.6	60
90[1]	1°	10	117.2	1.96	60
130[1]	30′	6	97.8	1.63	60
Mean values.		11.3	141.0	2.3	

[1] Altitude estimated to be 60 miles or 96.6 kilometers. In the other three cases the meteor trains were observed from two or more stations widely apart and the altitudes measured. No. 80 was without any question affected by rapid drift of the atmosphere (125 miles per hour), and hence gives too large a value for diffusion. In all probability the mean diffusion rate of both 20 and 80 is much too high. The numbers in the first column refer to the writer's meteor train catalogue. No. 87 was observed at two stations but the height has not been calculated.

Fig. 8 shows the method of calculating the mean diffusion rate of the train when its diameter is known at a definite time after its formation. This of course gives only the average diffusion. The particular train used in this illustration was No. 87, observed by R. M. Dole of Jamaica Plain, Mass., in 1901, and also shown in *D*, Fig. 9. On the assumption that the altitude of the train was 60 miles (96.6 kilometers) the train was 1.9 miles (or 3.06 kilometers) broad. From this it follows that the gas particles of the train diffused 1530 meters in 16 minutes, or at the average rate of 96.0 meters per minute, or 1.6 meters per second, the diffusion probably being very much greater at first.

The rate of diffusion is supposed to be inversely proportional to the pressure but directly proportional to the square of the absolute temperature, and according to the rates for diffusion at atmospheric pressure and normal temperature for ordinary gases would give a rate at very low pressure and low temperature about the same order as that shown by meteor trains, but nothing more definite can be said at present.

The diffusion of the afterglow formed by the electrodeless discharge is of the same order also, but definite experiments have not been made in that direction. When laboratory experiments are completed along these lines, and accurate meteor observations made,

both of which should not be difficult, the matter will assume a more precise character.

In regard to the observation of meteor trains for diffusion, a good instrument to use would be a small telescope such as a comet finder, for example, 40 magnifying power, with some micrometer device for measuring the width of the train in successive intervals of time after its formation.

The diffusion soon after the formation of the train is desirable, because if there is a high velocity of atmosphere drift at the time, for example, 100 kilometers per hour, the train will be soon distorted by air currents. Also it is important that the diffusion at different parts

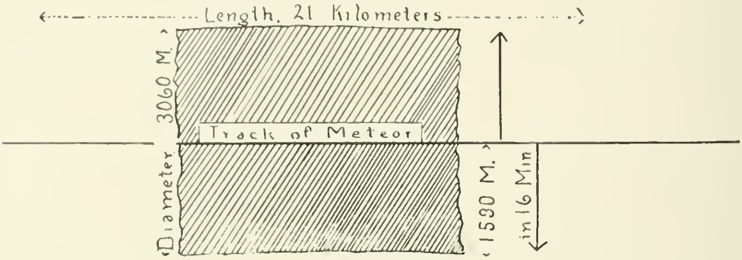

FIG. 8.—Showing the Rapid Diffusion Rate of a Meteor Train.

of the train be measured, because it appears probable from the descriptions and drawings of meteor trains that have been made that there is greater diffusion at the upper end of the train than at the lower as indicated by the trains shown in Fig. 9.

This apparent effect may not be real owing to the effect of perspective, for there are many drawings of trains which are quite cylindrical in appearance. It would be well for meteor observers to make special note of this matter in future.

Trains shown in Fig. 9:

A. Train observed at Sunderland, England, by T. W. Backhouse, November 14, 1866, 2:21 A. M. (*British Association for the Advancement of Science Reports*, 1867, p. 37.)

B. Train observed over the Persian Gulf, June 9, 1883, 7:51 P. M., by H. Harrison. (*The Observatory*, 6, 271, 1883.)

C. Train observed at Sunderland, England, by T. W. Backhouse, November 14, 1866, 2:41 A. M. (*British Association for the Advancement of Science Reports*, 1867, p. 377.)

D. Train observed at Jamaica Plain, Mass., by R. M. Dole, November 15, 1901, 5:09 A. M. (*Popular Astronomy*, **10**, 53, 1902.)

E. Train observed at Sunderland, England, by T. W. Backhouse, November 13, 1888, 5:19 A. M. (*Monthly Notices*, 49, 66, 1888.)

F_1. Daylight train, eastern United States, observed by J. S. Helles, August 24, 1869, after sunset. (*British Association for the Advancement of Science Reports*, 1870, p. 89.)

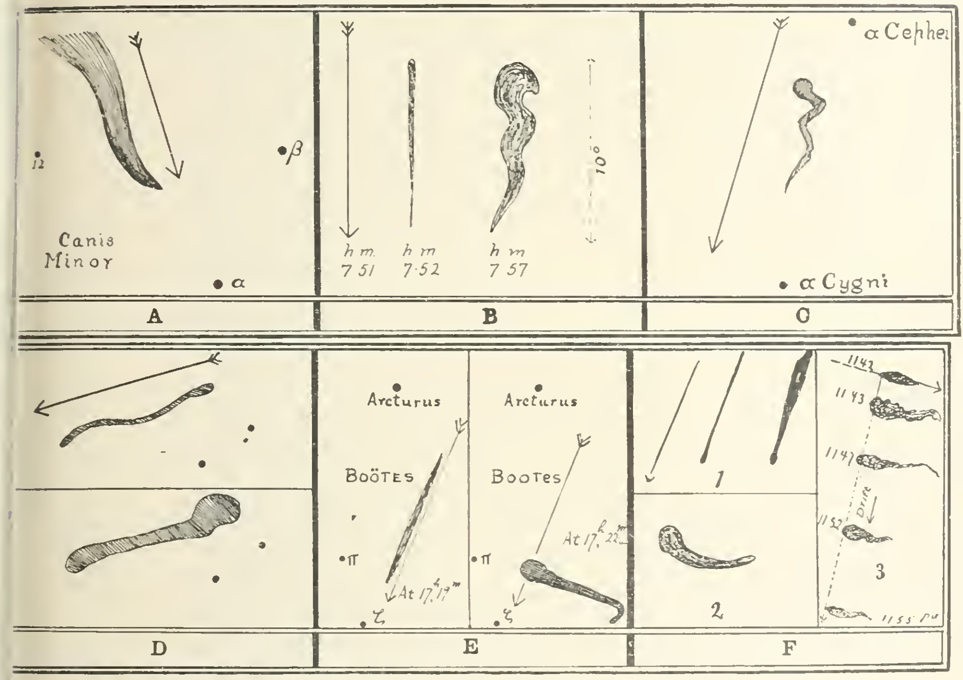

FIG 9.—Trains Which Indicate a Greater Diffusion Rate With Increase of Altitude

F_2. A train seen at Wishbeach, England, by S. H. Miller, Nov. 14, 1866, 3:07 A. M. (*British Association for the Advancement of Science Reports*, 1867, p. 319.)

F_3. Train observed at Bristol, October 13, 1900, 11:42 P. M., by W. F. Denning. (In letter to writer and not previously published.)

VII. THE DRIFT OF THE ATMOSPHERE AT GREAT ALTITUDES

In making a search for facts relating to meteor train phenomena, in the case of more than sixty trains it was found that the drift of the train over the surface of the earth had been observed. The

directions have all been reduced to points of compass, and the summary shows that, of the daylight meteors, seven out of nine trains illuminated by the sun drifted toward the west. These were probably at a lower altitude than 50 miles. Fifty-three trains observed at night, and probably at an altitude below 45 and 65 miles, drifted in various directions as follows: North 10, northwest 4, east 12, southeast 12, south 6, southwest 4, west 0, northwest 2; and in two different directions in different strata, 3. The facts appear to confirm Barnard's view that there is an easterly current over the North Temperate zone, for the currents predominate in that direction, but it was found that many trains drifted north and south and even to the northwest and southwest.

The facts also indicate that there are often zones of calm of perhaps 5 to 10 miles in depth, while directly above and below may be swift air currents, and that there are usually several zones with currents in opposite directions in the region above 30 miles altitude. The observations in England and Scotland show that 15 in 21 trains drifted toward the southeast quarter of the compass (E., SE., or S.), while in the United States 21 in 32 trains drifted toward the northeast quarter (E., NE., and N.), indicating a probable difference in the predominating upper drifts corresponding to different latitudes. A paper giving the facts of the train drifts in detail will appear in the *Monthly Weather Review.*

VIII. RESEMBLANCE OF THE METEOR TRAIN TO THE AFTERGLOW PRODUCED BY THE ELECTRODELESS RING DISCHARGE

The self-luminous train resembles the afterglow produced in a gas by the electrodeless discharge in the following points:

1. The meteor train as well as the afterglow appears to be produced between definite low gas pressures; in the former case the atmospheric pressures corresponding to the altitudes between 50 and 60 miles, in the latter the air pressure in the discharge tube between 0.5 and 0.05 mm.

2. The rate of diffusion of the afterglow at certain pressures is of the same order as the outward diffusion of the glowing particles of the meteor train, or at about the rate of a hundred meters per minute.

3. The visible spectrum of both the afterglow and the meteor

train is chiefly composed of a few lines or narrow bands. The spectra of meteor trains observed by Herschel and von Konkoly are recorded as consisting of a yellow line and a green line, attributed to sodium and magnesium respectively, but the identification was not quanitatively determined.

4. Under certain conditions the afterglow appears to die out first where it is formed, and observations have shown that many meteor trains are tube-like, and it is possible that they may fade first in the center, or directly in the meteor's track where the train originates.

5. The afterglow can occur in air cooled to $-186°$ C. The glow from the meteor train proceeds from a mixture of gas and extremely fine meteoric dust at the very low night temperature which exists at 50 or 60 miles above the earth's surface.

6. The afterglow is supposed to be produced by a polymerised gas gradually returning to its former condition accompanied by radiation.

The motion of the meteor through the atmosphere produces a temperature of many thousands of degrees centigrade, and may bring about chemical or physical changes in the composition of the atmosphere which on gradually reverting to its original state gives out a phosphorescent glow. It is not unlikely that the phosphorescence is connected directly with the highly ionized state of the air produced by the very high temperature of the nucleus, the effects being intensified by static electrical conditions, which are probably of considerable magnitude, produced by the rush of the meteor through the air with a velocity of from 20 to 30 miles per second.

IX. SUMMARY OF THE CHIEF RESULTS OBTAINED

A summary of some of the results of the investigations concerning meteor trains is as follows:

1. The meteor trains are self-luminous gas clouds combined with very minute meteoric dust particles, the latter in daylight reflecting light like ordinary clouds.

2. The height of meteor trains seen at night appears to be at a definite altitude, indicating that the phosphorescence is dependent on the gas pressure where the trains are formed.

3. The diffusion of the train is gas diffusion and its rate depends

on the pressure and temperature of the atmosphere, and probably on the initial intensity of the train.

4. Many meteor trains appear to be tubular in form, that is, the luminosity is greatest near the border.

5. Experiments have been made by the writer which give the law for the rate of decay of the phosphorescence of air at very low pressures, and these experiments explain the long visible duration of the meteor train, on the hypothesis that it is a phosphorescence which decays according to the same law.

6. Statistics on the color of trains show that, excluding those illuminated by sunlight, trains are as a rule green or yellow fading to white, colors which are typical of the phosphorescence of air.

While it is not at all certain that the light of the meteor trains is a gas phosphorescence that is identical with the afterglow which follows the electrodeless ring discharge, yet the phenomena are similar in many respects. It is hoped that precise spectroscopic observations can be obtained of a meteor train and the positions of the yellow and green lines observed by Herschel and von Konkoly exactly determined. The latter observed the green line to last for over ten minutes in the case of one train. The photographic spectrum of the meteor nucleus should contain the bright lines of the train combined with a continuous spectrum and bright lines from the incandescent nucleus, but it is likely that the train spectrum would be relatively feeble.

I desire to express my thanks to the members of the Astronomical Staff at Columbia University who have placed the facilities of their department at my disposal and have kindly assisted me on various occasions.

Phoenix Physical Laboratory
Columbia University
June 1907

ON THE DOPPLER EFFECT IN THE SPECTRUM OF HYDROGEN AND OF MERCURY

COMMENTS ON MR. STARK'S ARTICLE

By G. F. HULL

Paschen's confirmation of Stark's result regarding the existence of the Doppler effect for the mercury lines makes it clear that under certain conditions some of the luminous particles of mercury in the canal stream of that gas are in rapid motion. In some preliminary measurements made eighteen months ago I found a shift of the mercury lines from the canal stream. The result was announced in the *Proceedings of the Royal Society* of June 1906. But a large number of plates taken later showed no shift. In these later experiments higher potentials were used and greater care was exercised to eliminate errors due to temperature changes and vibrations. Moreover, I failed to observe a Doppler effect for helium (except a very small one); so I was led to the conclusion that my first results in the case of mercury were accidental, and that in general the luminous mercury particles in the canal stream were not in motion.

To account for these negative effects in mercury and helium I advanced the hypothesis that the stream of positively electrified particles, when mercury or helium filled the tube, was not composed of the particles of either of those gases, but was probably composed of hydrogen, the particles of which are easily positively electrified and set in rapid motion. That hypothesis has been confirmed, not only by experiments which I have conducted during the past winter but also and chiefly by the investigations made by J. J. Thomson and published in the *Philosophical Magazine* for May 1907. Professor Thomson found that

> whatever kind of gas be used to fill the tube, or whatever the nature of the electrode, the deflected phosphorescence (caused by the canal stream) splits up into two patches. For one of these patches the maximum value of $\frac{e}{m}$ is about 10^4, the value for the hydrogen atom; while the value for the other patch is about 5×10^3 the value for the α particle or the hydrogen molecule. . . . . The interest of the experiments at very low pressures lies in the fact that in this case the rays

are the same whatever gas may be used to fill the tube; the characteristic rays of the gas disappear, and we get the same kind of carriers for all substances (p. 573).

In the case of helium under certain conditions, Professor Thomson found that there was a third particle acting as carrier, viz., a particle of the size of the helium atom. But helium was the only gas among oxygen, nitrogen, carbonic oxide, hydrogen, helium, neon, showing a characteristic ray, and even helium ceased to be an exception when the discharge potential was high. Professor Thomson does not state that he tried mercury vapor but I infer from his article that he would expect to find a motion of the mercury atoms, if at all, only at small discharge potentials.

It seems clear from these experiments that the particles of the gas (excepting hydrogen) filling the tube need not be, and at higher potentials probably are not, the carriers of the current. That was my inference based upon my observations on the canal streams of hydrogen, mercury, and helium.

We are thus confronted with conflicting testimony. From Professor Thomson's experiments we should not expect a Doppler effect in the positive rays of nitrogen. But Stark and Hermann have announced that they have found such an effect. In the case of helium I found that, for the conditions under which I worked, the Doppler effect, if it existed at all, was very small. Confirming this, Professor Thomson shows that a condition exists where the helium particles do not move. But there are other conditions where the helium particles move rapidly, and consequently for these conditions a large Doppler effect should be found. Apparently Dr. Rau[1] has been for-

[1] The only statement published so far by Dr. Rau regarding the Doppler effect in the canal stream of helium is as follows: "Mit der eben angeführten Hypothese stimmt überein dass die Heliumkanalstrahlen nach meinen Beobachtungen den von Herrn Stark entdeckten Dopplereffekt nicht oder doch nicht in der zu erwartenden Grösse zeigen. Ich konnte ihn unter Benutzung eines Kirchhoffschen Spektralapparates mit vier Prismen trotz der grossen Helligkeit des Spektrums weder bei subjektiver Beobachtung noch auf Photographien (bis 15 Stunden Beleuchtungszeit) wahrnehmen; eine nähere Untersuchung musste natürlich mit dem Gitter erfolgen." —*Physik. Zeit.*, 7, 423, 1906.

The optical system used by Dr. Rau was sufficient to have shown the Doppler effect expected in the case of helium had it existed, viz., a few Ångström units. The potentials he used were high enough. The conclusion is therefore that very few luminous helium particles were carriers of the positive charges.

tunate in working with these conditions. In the case of mercury vapor I found no certain Doppler effect. Professor Thomson's experiments lead us to expect no effect for high discharge potential. But Professor Stark claims that the effect is found only when the potentials are high. It is obvious that our experimental evidence is not complete in regard to the conditions under which the Doppler effect may be present or absent.

There are other points in which my results do not agree with those obtained by Professor Stark. I found no polarization of the light from the canal stream, while Professor Stark claims that a polarization exists. I found no shift of the lines of the canal spectrum of hydrogen, viewed at right angles to the direction of the stream, in comparison with the lines from a Plücker-tube spectrum. Professor Stark found that the canal-spectrum lines of hydrogen, so viewed, are displaced toward the red when compared with the slow-moving lines of the negative glow. The displacement seems to be proportional to the wave-length and also to the square of the velocity. The displacement of the center of $H\beta$ is approximately 0.8 Ångström units for a velocity of 1.2×10^8 cm. sec.$^{-1}$.

Obviously in view of so many discordant results one should be slow to construct elaborate theories in regard to the canal rays. I feel like quoting in this connection a statement made by Lord Rayleigh in a recent number of the *Philosophical Magazine:* "There is much in the behavior of vacuum tubes which at present defies explanation."

In conclusion I wish to note that, if the spectrum of the mercury lines from the canal stream consists of a strong stationary line accompanied by a broad, faint, displaced component, the echelon-prism which I used would not be a satisfactory analyzer of the radiation. For the faint component would appear as a very broad hazy line, near the center of which would be the strong line. This was a result for which I was constantly on the lookout, but which I did not detect. Nor did I find a faint displaced component on the few test plates taken with a 60° prism.

Dartmouth College
June 26, 1907

NOTE ON DISPLACEMENT OF SPECTRAL LINES

By J. LARMOR

The important paper by Mr. Humphreys (this Journal, **26**, 18, July 1907) gives data for somewhat closer scrutiny of the origin of the pressure-shift of lines in the spectrum. The change must be connected with electric properties of the surrounding gas; mechanical pressure arises merely from the translatory motions of the molecules, and these are so slow as hardly to count in connection with radiation-periods. Thus the phenomenon is probably more strictly describable as a density-effect. Electrically, the effect of increase of density is to increase the inductive capacity of the medium, that is, to diminish the effective aethereal elasticity which propagates the radiation. This is the averaged result; each molecule individually, through the agency of its plastic field of force or aether-strain, provides a yielding region in the aether in which the effective stiffness is diminished. The elastic energy which maintains the free vibrations of a radiator is located in its field of force in the adjacent aether; and by dynamical principles any loosening of the constraint in that field such as an adjacent molecule would produce, which would itself be somewhat intensified by equality of period, must in general tend toward increasing the free period, involving displacement of the radiation toward longer wave-length.

By known dynamical principles[1] the change in free period due to slight change of constitution of the vibrating system can be estimated, by calculating the altered kinetic and potential energies of the type of vibration under consideration on the assumption that the type remains unaltered.

In the present case some light may be thrown on the amount of effect to be expected, by supposing the vibrating molecule to be situated in the center of a sphere of free aether, beyond which the molecularly constituted gas is taken to be smoothed out into a uniform medium having the inductive capacity K of the gas. The type of vibration being retained as before, its kinetic (magnetic) energy is not thereby

[1] On this subject see Lord Rayleigh's *Theory of Sound*, §88.

affected from what it would be in a vacuum, but its elastic (electric) energy is altered in the ratio K^{-1}, wherever K is different from unity. To obtain a rough estimate, suppose the vibrating aether-field to be that outside a concentric spherical surface of radius a, and suppose the electric field to fall off with distance according to the law r^{-n}, multiplied of course by a function of direction. The static energy in it, measured from outside up to a concentric spherical surface of radius c, will be proportional to

$$\int_c^\infty r^{-2n}\ 4\pi r^2 .\ dr,\ or\ \frac{4\pi}{2n-3} c^{-2n+3}.$$

If therefore the region beyond a distance c, equal say to ka, is filled with material of inductive capacity K, not much different from unity, the total static energy of the vibration is thus altered in the ratio of

$$a^{-2n+3} - c^{-2n+3}(1 - K^{-1}) \text{ to } a^{-2n+3},$$

that is, of $1 - k^{-2n+3}(1 - k^{-1})$ to 1. The frequency of the vibration is increased as the square root of this. For air at pressure of one atmosphere $K = 1.0006$, and Mr. Humphreys gives (p. 31) the proportionate change of wave-length as about 10^{-6}. Thus $k^{-2n+3} \times 0.0006$ is about equal to 10^{-6}. If the vibrator operates as a simple Hertzian doublet, $n \doteq 3$; the other term, which constitutes the radiation, not being of account close to the vibrator. This would make k^{-3} of the order of $\frac{1}{600}$, so that k would be about $8\frac{1}{2}$. In a gas at pressure of one atmosphere the molecules are spaced at a mean distance of very roughly 10 times the molecular diameter; and if $n = 3$, only about $\frac{1}{27}$ of the energy of one of them is beyond three molecular radii from its center. Thus it is not unreasonable to replace the influence of the discrete distribution of gas-molecules by that of a uniform averaged medium extending inward to about eight molecular radii from the center of the vibrator. But these *data* are of course far too vague to justify more than the mere statement that the dielectric influence of the neighboring molecules is a *vera causa* of the right order of magnitude. For the next higher type of possible vibration, $n = 4$, the value of k would be about $3\frac{1}{2}$, which may be just barely permissible; but for $n = 5$, the value of k would be slightly over 2, which would be ruled out. There is thus some presumption that the free vibration corresponding to each line of the spectrum is (except

of course close up to the nucleus) of the simple type of that of a Hertzian doublet source. Moreover if n were not 3, the effect would not be proportional to the density of the gas. We have been estimating the average effect, on which a general broadening of the band due to irregular nearer approaches of molecules is superposed.

The shift has not been observed in band spectra. The vibrator would then presumably be a molecule; and it may not be fanciful to suppose that this circumstance may point to its field of energy being more concentrated into the region between its atoms; a higher value of n would make the difference.

The remarkable one-sided broadening of absorption bands of pure mercury vapor, and its abolition by the admixture of a foreign gas, reported by Professor Wood (this Journal, **26**, 41, July 1907) may perhaps have suggested similar considerations. The tendency to condensation in the pure vapor may proceed to an equilibrium, when the formation of loose molecular aggregates by what may be called adhesion would be balanced by their destruction by collisions. The molecules in such loose aggregates would, owing to their (slight) mutual influence, vibrate in longer periods, and give rise to the displaced part of the band: but the average amount of this incipient aggregation would be much diminished by the admixture of a neutral gas.

CAMBRIDGE, ENGLAND
August 8, 1907

THE VARIABILITY IN LIGHT OF *MIRA CETI* AND THE TEMPERATURE OF SUN-SPOTS

By A. L. CORTIE

The existence of a banded spectrum in that of sun-spots was first detected in the green region of the spectrum by Secchi in 1869,[1] and in the red by Professor Young in 1872.[2] In the years 1880–1883 many observations of similar bands in the green were made by Mr. Maunder at Greenwich.[3] The bands in the red first seen by Professor Young were independently observed as flutings and their positions ascertained by the Stonyhurst observers in 1885–1886.[4] Flutings are characteristic of the spectra of chemical compounds. Professor Young was led to the conclusion, adopted also by the Stonyhurst observers, that the banded spectrum in sun-spots "would seem to point to such a reduction of temperature over the spot-nucleus as permits the formation of gaseous compounds by elements elsewhere dissociated."[5] Whether the compounds are gaseous or not is beside the question at present discussed, the point insisted upon being that according to this view sun-spots are at a lower temperature than the neighboring photosphere. The recent more elaborate and more precise work carried on both in laboratory and observatory by Professor Hale with Mr. Adams and Mr. Gale at Mount Wilson, California,[6] and by Professor Fowler at South Kensington[7] has served to strengthen the probability of this view. The bands especially observed at Stonyhurst in 1885–1886, were not seen in the spots observed from the autumn of 1886 to that of 1890.[8] It is possible that such bands are a characteristic of sun-spots at the periods near and at maximum spot-activity. They have been recorded, however, in all recent obser-

[1] *Le Soleil,* 2d ed., Vol. I., p. 288.

[2] *Nature,* 7, 107, 1872.

[3] *Greenwich Photographic and Spectroscopic Results.*

[4] *Monthly Notices,* 47, 19, November 1886.

[5] *Nature, loc. cit.*

[6] *Astrophysical Journal,* 24, 185, October 1906.

[7] *Transactions of the Solar Research Union,* Vol. I, pp. 201–229.

[8] *Monthly Notices,* 51, 76, 1890.

vations by Mitchell at Princeton, Fowler at South Kensington, and at Stonyhurst, and are a marked feature in the superb map of the spectrum of sun-spots recently distributed to observers by the generosity of Professor Hale and Mr. Ellerman. Perhaps only the bands at the red end of the spectrum disappear at the approach of minimum sun-spot activity; a point which needs investigation.

With regard to the origin of the bands seen in the spectrum of sun-spots, Professor Hale and Mr. Adams have identified bands in the deep red, with heads at λ 7054.6, 7088.0, 7125.9, as due to titanium oxide,[1] while more recently Professor Fowler has traced a series of bands in the green as due to magnesium hydride.[2] The existence of spectra of chemical compounds as giving rise to the phenomena of bands in the spectrum of sun-spots is now indubitable. The main purport of the present paper is to show that if we argue from the differences in the spectra of the stars which are generally assigned to temperature as their cause; and especially if the argument be founded on such stars as contain the same chemical compound as has been found to exist in sun-spots, that such a line of argument will tend to strengthen the presumption as to the relatively lower temperature of sun-spots, when compared with that of the photosphere.

The spectrum of stars of Secchi's Type III is characterized by a series of dark bands. These bands were numbered and measured by Dunér, and are known by his name. Stars of this type which show the characteristic bands are *α Herculis*, *α Orionis*, and the variable star *Omicron* or *Mira Ceti*. The bands in *α Herculis* and *ο Ceti* were shown to be due to a compound of titanium by Professor Fowler.[3] This compound of titanium was subsequently proved to be titanium oxide by the same observer. The spectrum of titanium oxide has also been recently recognized in the spectrum of *α Orionis* by Mr. Newall and Mr. Cookson,[4] with the heads of three flutings practically coincident in wave-lengths with those given by Hale and Adams as present in the banded spectrum of sun-spots at λ 7054.6, 7088.0, 7125.9. Hence a connecting link is furnished between the banded

[1] *Astrophysical Journal*, **25**, 77, 1907.

[2] *The Observatory*, **30**, 272, July 1907,

[3] *Proc. R. S.*, **73**, 219, 1904.

[4] *Monthly Notices*, **67**, 482, 1907.

spectrum of stars of Type III and that of sun-spots; and such changes observed in the banded spectrum of the stars of this type as are presumably due to changes of temperature, may serve to throw light upon the question of the temperature of sun-spots. A very complete account of the spectrum of *Mira Ceti* as observed at Stonyhurst at its maximum of 1897 was given by Father Sidgreaves,[1] accompanied by tables of wave-lengths of the bright and dark lines, and of the dark bands. The greatest brilliancy of the star at this maximum was about 3.0 magnitude.[2] At the recent maximum of December 1906, the star attained its greatest luster on the 11th, and reached the higher value of 2.0 magnitude;[3] that is, it was two and a half times as bright and one and a quarter times as hot in 1906 as it was in 1897. A comparison of the two series of plates of the spectrum of the star, secured by Father Sidgreaves at the two maxima, under precisely identical conditions as to the instruments and plates employed, shows a striking change in the relative intensities of the bands. Fourteen bands were mapped between $H\gamma$ and $H\beta$ in the spectrum of 1897, with sharp heads toward the violet, and wings of gradually diminishing intensity toward the red. The positions of the heads of these bands were:

No.	λ	No.	λ
1	4352	8	4623
2	4395	9	4667
3	4420	10	4713
4	4458	11	4735
5	4502	12	4757
6	4544	13	4803
7	4581	14	4842

In the spectrograms of 1906, the bands numbered 3, 4, 7, 8, 9, 10, 11 are much weaker than in 1897, while those numbered 1, 2, 5, 6 are very much reduced in intensity; in fact numbers 1 and 2 are hardly visible. Yet the character of the bands named remained the same. In the case, however, of bands 12, 13, 14, the winged extensions have altogether disappeared in 1906, leaving strong lines, the

[1] *Ibid.*, **58**, 344, 1898.

[2] *Journal B. A. A.*, **8**, 283, 1900.

[3] *Ibid.*, **17**, 346, 1907.

heads of the original bands, at the wave-lengths named. A brighter maximum in the visibility of the star would presumably indicate that the star is hotter, as well as more luminous, and it is a significant fact, as bearing on the temperature of sun-spots from the bands observed in such spectra, that the difference of about a full magnitude in the light of the star between the maxima of 1897 and 1906 should have resulted in a corresponding decrease in the intensity of the titanium-oxide absorption bands, which compound also gives rise to a banded spectrum in sun-spots.

The $H\beta$ line, which was almost if not entirely extinguished by the possible overlapping of the band λ 4842–4884 in 1897, was prominently visible in 1906, while the other lines in the series from $H\beta$ to $H\sigma$, with the exception of $H\epsilon$, covered by the calcium absorption, were easily identified on the plates. The lines $H\gamma$ and $H\delta$ were also winged, presenting an appearance somewhat like that, though on a greatly reduced scale, seen in the hydrogen lines at the outburst of the stars *Nova Aurigae* and *Nova Persei*, as investigated at Stonyhurst. This character of the hydrogen lines $H\gamma$ and $H\delta$, not seen in 1897, also accentuates the much greater luminosity, and concomitant rise in temperature of the star at the last maximum.

Again, the gradual transition of the banded spectrum of *o Ceti* to the line spectrum of Type II, or solar stars, through such connecting links as *α Herculis*, *β Pegasi*, *η Geminorum*, *α Orionis*, *β Andromedae*, and *α Tauri* was demonstrated in 1897 by Father Sidgreaves,[1] who also showed that it was more remote from the solar spectrum than the typical star of Type III, *α Herculis*. The gradual deepening in intensity of the bands as the series passes from *α Tauri* to *o Ceti* would point to a gradual lowering of temperature, when considered together with the greater darkness of the bands of *o Ceti* at a less maximum of brightness. This view coincides with the classification adopted by Sir Norman Lockyer, in which the Aldebarian stars are a step higher on the ascending scale of temperature than the Antarian or stars of Type III.

In a recent paper on the "Spectrum of *Mira Ceti*,"[2] Mr. J. S. Plaskett writes:

[1] *Monthly Notices, loc. cit.*

[2] *Journal of the R. A. S. of Canada,* 1, 56, 1907.

The only absorbing elements present in the strong and best defined lines, ... are *Ti*, *V*, *Fe*, *Mn*, *Cr*. . . . . the first specified are those which are most strongly affected in the spectra of sun-spots, and which, as Professor Hale and Mr. Adams have shown, are much intensified in the spectrum of *Arcturus*, and still more so in α *Orionis*, as compared with their intensity in the sun. Apparently they are even more prominent in *o Ceti* than in α *Orionis*. . . . .

Here again is a further link of similarity between the spectrum of sun-spots and that of *o Ceti*.

Hence, to sum up, the undoubted presence of the chief constituents of the line spectrum of sun-spots as intensified in stars of Type III; the presence of the bands of titanium oxide, also recognized in sun-spots; the partial disappearance of some of these bands, and the total disappearance of others at the greater luminous maximum of *Mira Ceti* in 1906; and this, too, accompanied by a behavior in the hydrogen lines akin to that observed in new stars; the substitution of a line for a banded spectrum in a series of stars on an ascending scale of temperature; these are all facts which, when linked together, point to the conclusion that the temperature of sun-spots is lower than that of the solar photosphere.

Stonyhurst College Observatory
July 1907

Minor Contributions and Notes

PORTRAIT OF SIR WILLIAM HUGGINS

The portrait of Sir William Huggins which adorns this number of the Journal is reproduced in photogravure from the painting by Hon. John Collier presented to the Royal Society by certain subscribers on November 30, 1905, at the completion of Sir William's tenure of office as president (1900–1905). The sittings were made at the rooms, and in the presidential chair, of the Royal Society, when the distinguished subject was eighty-one years old. Excepting the immortal Newton, only two others have held this office at so great an age.

The continued activity of many of its pioneers has been one of the compensations for the youth of the science of astrophysics: may this fortunate condition long endure!

We do not here enter upon any discussion of the scientific achievements of Sir William and his gifted collaborator, Lady Huggins, for are they not written in the *Philosophical Transactions* and *Proceedings* of the Royal Society, in the *Monthly Notices* of the Royal Astronomical Society, in the noble volume of *Publications* of the Tulse Hill Observatory, and in the pages of this Journal, as well as in numerous public addresses?

The thanks of the editors are due to the artist and to the committee of subscribers for permission to publish a reproduction of this splendid portrait.

BAND SPECTRUM OF VANADIUM

At the end of their most interesting paper on sun-spot spectra[1] Messrs. G. E. Hale and W. S. Adams make the following remark on the band spectrum of vanadium: "Hitherto we have not been able to produce a vanadium band spectrum in the laboratory." Using vanadium chlorate I have never found any difficulty in getting a band spectrum in the arc and even in the spark (with self-induction), that seems to belong to the metal or to the oxide. Professor Hagenbach and I have given a short notice on this band spectrum on p. 37 of our *Atlas of Emission Spectra*, Jena and London, 1905, together with a reproduction of a plate taken with a grating of 1-meter radius; unfortunately all the details of the originals are lost, even in the heliogravures, and only three heads are to be seen in the green and yellow parts of the spectrum.

Two remarks are to be added: first, that there is still some uncertainty about the substance to which the band spectrum belongs; second, that I only wish to facilitate further and more accurate study of the vanadium spectrum by this note, without any claim of priority, although I have not found an allusion to the band spectrum in the papers of Rowland and Harrison, Hasselberg, Lockyer, Exner and Haschek, and Lohse on the arc spectrum of vanadium.

H. KONEN

UNIVERSITY MÜNSTER I W.
June 17, 1907

[1] "Second Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Astrophysical Journal*, **25**, 75–95, 1907.

The melancholy announcement has just reached us of the death, on August 13, of Hermann Carl Vogel, the eminent director of the Royal Astrophysical Observatory at Potsdam. Although the condition of his health has given concern to his friends for some years, this fatal termination of his malady, at the comparatively early age of 65, comes as a shock to us who had hoped that he might yet enjoy many years of fruitful activity in the important position which he had filled for a quarter of a century.

A sketch of the life and work of Professor Vogel will appear in an early number of this Journal, of which he had been an associate editor, or collaborator, since its foundation.

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THE CANALS OF MARS, OPTICALLY AND PSYCHOLOGICALLY CONSIDERED

A REPLY TO PROFESSOR NEWCOMB

By PERCIVAL LOWELL

When my revered master, the late Professor Benjamin Peirce, asked me at graduation from Harvard to return to the university to teach mathematics with a view to becoming eventually professor of the subject there, I refused because I preferred not to tie myself down—not because mathematics had not always appealed to me as the thing most worthy of thought in the world. Indeed, subsequent companionship with this, perhaps the most attractive of all the muses, has impressed me with two qualities about her of fundamental importance in any inquiry, both of which find exemplification in the article to which I am about to reply. The first of these is that mathematics is merely formalized logic and deals not with the matter concerned but with the manner of its manipulation. If you put peascods into a machine you cannot take out flour, however fine you grind. Or, to drop analogy, if you apply mathematics to physics or optics, you must first be sure your physical data are correct before you proceed to deduce results from them. The second fact about mathematics is that it is a quantitative, and not simply a qualitative, instrument. Now, in the cosmos, quantity—size, length, duration—is of the very essence of things and processes. A body with twice the diameter of another does not behave under similar conditions—stress, temperature, motion—with twice the action of the first. Or, to take another

kind of example, an invention may work beautifully on one scale to fail completely on another. It is not enough, therefore, to examine a matter qualitatively; to reason quantitatively is vital to reasoning aright.

Before proceeding to take up Professor Newcomb's article on "The Optical and Psychological Principles Involved in the Interpretation of the so-called Canals of *Mars*,"[1] which I am about to answer, it is a source of pleasure to note two things in it: first, that it shows how much the subject of recent Martian investigation has excited interest in scientists not themselves specialists in the subject; and secondly, how completely the general attitude of incredulity has altered for the better in the last ten years. In addition, it is pleasant to perceive that Professor Newcomb recognizes the importance of critical experiments on all points, even hinting at illusion, and appreciates the great care that has been taken at this observatory to examine and prevent any such possible mistakes.

To deal now with the points he has raised in the order in which he raises them: The first relates to the fact that any so-called achromatic objective causes of necessity rays of different colors to come to a focus at different focal distances and consequently that if any monochromatic image be focused on, it must perforce be surrounded by others out of focus and therefore distended in area. This, of course, is true, but Professor Newcomb then goes on to argue numerically from it without noticing the omission of two factors in the problem which entirely change the results at which he would arrive. The first of these is that the very fact that the out-of-focus images cover more area dilutes their effective character and *as the square* of their diameters. Secondly, the intensities of the various colors as light for the eye is not, as his computation tacitly assumes, equal at the start; but, on the contrary, form a curve sharply rising from invisibility in the ultra-violet to a sort of flat-topped cone in the yellow, to fall with like abruptness to disappearance in the infra-red. In other words, the eye itself discards to a great extent what is out of focus. Each ray has to be multiplied by $\frac{1}{(F_1 f)^2, F_2 f}$, where F is a function depending on the color-curve of the objective, and F_2 that of the sensitiveness

[1] *Astrophysical Journal*, 26, 1–17, July 1907.

of the human eye to the focal length f of any ray—and then the several rays integrated for so much of each as falls within the distance s, before the least approximation can be made either to the amount of light as regards the eye within a circle of radius $0''.10$, or to the blurring effect of the unfocused to the focused portion. So that Professor Newcomb's determination is not even an approximate solution of the problem.

The effect of these two factors is to produce a curve of intensities of the special colors for the eye quite other than he considers to be the case and not very unlike that of the intensity of the diffraction pattern for a circular aperture. Now every observer of double stars is aware that a striking feature of the spurious disc made of a point of light by a lens is the clear-cut character of its edge. Instead of fading off gradually the light ends abruptly, to begin again sharply in the first bright ring. Thus experience shows that the eye takes account only of certain intensities, refusing to perceive the rest. And this is explained by the introduction of the two factors omitted by Professor Newcomb.

Thus we see that Professor Newcomb's investigation is theoretically incorrect because of the omission of two factors vital to the result. Let us turn from this to the published experience of an expert optician. For it has escaped Professor Newcomb's notice that this subject has been not only theoretically but practically treated with much care already by a man who stands high in his profession, to wit, by the optical manager of Messers. Cooke & Sons, Mr. H. Dennis Taylor.[1] Although the whole paper is pertinent to the subject, the following brief quotations will suffice:

Now it happened to occur to me that I would determine the limits of good focus, not only theoretically, by application of the usually accepted rule, but I would also confirm it by experiment. What, then, was my surprise when I found that, so far from there being any agreement between the tacitly accepted theory and actual fact, I actually had to push in the eye-piece or draw it out in order to expand the spurious disc into a penumbra of twice its size, by an amount equal to 0.03 inch on *each* side of focus, or *five* times as much as I had theoretically expected; while I could push the eye-piece in or out by 0.015, or nearly 0.02 inch, without sensibly increasing the size or destroying the character of the spurious

[1] *On the Adjustment and Testing of Telescopic Objectives*, T. Cooke & Sons, pp. 67–84; also "The Secondary Colour Aberrations of the Refracting Telescope—Relative to Vision."—*Monthly Notices of the Royal Astronomical Society*, 54, 67–84, 1893.

disk. This astonished me, and led me to make a series of experiments with different eye-pieces, apertures, and focal lengths and varying relations between apertures and focal lengths. The results turned out to be independent of the focal lengths of the objective and the power of the eye-piece, provided the magnifying power was sufficient to show the star disk.[1]

And below:

But here we have a fact which renders possible what before seemed impossible, viz., the production of a tolerably definite focus out of the confusion of many foci; for since the bundle of rays is nearly cylindrical for a distance of nearly 0.02 [inch] on each side of focus (when $\frac{f}{a} = 15$), evidently color aberrations to that amount on each side of focus will not give rise to loss of light owing to any part of it falling outside the limits of the star disc.[2]

Thus his tests are entirely opposite in conclusion from what is supposed to exist by Professor Newcomb.

Now let us see what takes place in practice at the telescope; for all our physical, in this case optical, knowledge is ultimately based on experience and experiment. As I said in the beginning of this reply, if we put into our equations wrong fundamental facts we shall only derive from them wrong conclusions. We will select, to start with, optical phenomena which have nothing to do with *Mars*, as being less open to criticism. In the clear and steady air of Flagstaff, the shadows of *Jupiter's* satellites upon the planet's disk stand out so sharply edged that they give the impression at first of being actual black spots in the focal plane of the eye-piece. This is in spite of possessing, of course, a true penumbra, apart from any telescopic effect. This clearly defined appearance has been noticed not by one only but by all the observers here. Secondly, ink lines have been ruled on paper of known widths and observed through the telescope at suitable distances to have them subtend angles analogous to planetary lines. They have uniformly been observed to be as dark and unfringed of shading as when seen close to by the naked eye. This is the consensus also of all the observers scanning them. Lastly, faint shadings are seen on some planets which are totally different in appearance from the "canals" of *Mars* as here seen. Thus on *Venus* such exist; and in the wisps between the belts of *Jupiter* (actually photographed here recently by Mr. Lampland) we have another variety which no practiced observer would liken to the Martian lines.

[1] Cooke, *op. cit.*, p. 74. [2] Cooke, *ibid.*, p. 77.

Thus, experience at the telescope, quite apart from anything to do with *Mars*, and experiment there as well, are definite in their pronouncement against Professor Newcomb's supposed optical effects.

Before leaving the optical part of his paper I may mention the causes of what he considers discrepancies in drawings between different observers. For none such are to be found here between observers working consecutively, though each at the time be ignorant of the other's delineations. Poor air is the first condition of seeming discrepancy and the cause of such drawings as show the lines broad and diffuse. It produces the same distortion that we mark over a hot stove, and in the case of fine detail spreads what would be dark and narrow into a wide grayish belt. This I know, not only from theory and inter-comparison of the drawings of others, but from having seen the effect produced and afterward subsiding at the telescope.

The second cause is seasonal change in the planet itself. The "canals" are not at all times equally conspicuous. Indeed, they undergo a regular annual metamorphosis, and what is more and very interesting and peculiar, they individually suffer what may be called hibernation for a greater or less length of time, up to one or more Martian years.

Turning now to the second portion of the paper—that dealing with psychological principles, we come to the second point I have spoken of as being vital, to wit, quantitative, as opposed to merely qualitative, investigation. A reader not conversant with the subject would suppose that the disk constructed by Professor Newcomb and observed at the given distances away represented in size and consequent suitability for depiction that of *Mars* as seen through the telescope when the scanning of this disk is most fruitful. In fact he so supposes it himself, as he tells the reader that "its breadth and distance were arranged so as to correspond to the apparent disk of *Mars* under the usual magnifying power." Calculation, however, will show this not only not to be the case but widely to differ from the fact. At this opposition the disk of *Mars* subtended 23″, and, of course when criticism of the linearity of its "canals" or of the fineness of its markings is in question, it is by the best not by the worst or even by the medium views of the planet obtainable that our knowledge of them is derived and therefore to be gauged. The lowest power with which observations here have been made of *Mars* at this opposi-

tion is one magnifying 391 diameters. With a power, then, of 391 and a disk of 23″, the apparent size of *Mars* is 149′.5 or 2°.5, five times the diameter and twenty-five times the area the moon presents to the naked eye. Now the disk used in Professor Newcomb's experiment was 38 cm in diameter and the distance at which it was used by the naked-eye observers was 30 meters and 100 feet. It subtended therefore but 44′, or less than a third of the diameter, and less than one-eleventh of the disk of *Mars*. In other words, *Mars* spreads an area to the observer's eye between eleven and twelve times that shown by the experimental disk. Interesting, therefore, as this experiment may be, it has no applicability to *Mars*. This any reader of the paper can easily prove to himself. In order for the disk as reproduced in the article to look as large as *Mars*, it must be viewed from a distance of 2.7 m (8.7 ft.). The observer will then find that not only is he under no liability of illusion to make of the discontinuous markings lines, but that he can see their shape and character with great nicety.[1]

The fact is that here quantitative treatment, or in other words, the scale on which the experiment is tried, is vital to any importance in the results we are to deduce from it. No one would dream of denying that there is a limit to detection of any detail whether telescopic or of everyday action. It is a truism. We cannot affirm that below that limit even a telegraph wire is continuous. In fact we know from the molecular theory of matter that it necessarily ultimately is not. In questioning, then, the apparent linearity of the "canals" of *Mars* it is necessary to make quantitative measures to realize where we stand. Now, such measures have been made at Flagstaff; and the experiments were made through the telescope. This is an important detail to be observed in all such investigations. When an astronomical fact is to be investigated experimentally, it is fundamental that the phenomena should be subjected to telescopic

[1] Even at the distance (30.3 ft.) corresponding for the reproduction to the erroneous distance at which the original was sketched, nearly four times as far off as it should have been, Mr. Slipher and the writer found with only a general knowledge of the reproduced disk no difficulty in making out its dotted character. The greater part of the supposed lines showed to the writer their composite character at once, thus failing to simulate the uniformity of the Martian canals; while in some instances he could see the actual breaks between the dots.

result. The only way to test the action of an unknown factor is to exclude all known factors of variation from the experiment, or, in other words, to vary the conditions only as regards the factor to be found. Self-evident as this is scientifically, it has not been put in practice generally by critics of the markings on *Mars*.

Now in this connection, to observe markings by transmitted light, as is suggested by Professor Newcomb, is to violate the above principle, well recognized as it is in all research. For the planet is lighted to us by reflected light and we must observe our experimental markings in the same manner if we would attain precision in our results. I may also say that in my paper on visibilities of fine lines, which Professor Newcomb quotes, not only was the *minimum visibile* determined, but the limits of visible inference, to wit, $0''.59$, in the case, which he missed in reading the paper. He will also be interested in knowing that the illusion to which he found himself subjected, that of seeing lines caused by shading on the paper, similarly presented itself to me many years ago in telescopic investigation of this very subject; but only when nearer the limit of contrast than is the case with the "canals" of *Mars*. Again the wire, which he supposes to have been black and from whose color he argues to his conclusions, was not black; so that the deductions in consequence fall to the ground. Furthermore, the results were practically the same when the experiments were repeated with dark blue[1] lines on a paper background, so that the sky was not in question. This emphasizes again the absolute necessity of quantitative measuring in the matter. For it is part of the profession of a trained observer to recognize just such points. And here I may correct an impression which Professor Newcomb, not being himself an observer of *Mars*, has received at second hand. He states that the background upon which the "canals" are seen is not uniform in the case of *Mars* and that therefore lines on paper are not a true criticism. This is an error due probably to his reading that the "seas" were a jumble of markings impossible to decipher. This jumble is the very canal and oasis system imperfectly seen, as I can state from having seen it resolved. It, therefore, cannot be used as an argument against its own detection after the fact—especially in the light regions where uniformity of tint is the rule. He was arguing

[1] *Lowell Observatory Bulletins*, Nos. 2 and 10.

from the observations of a sensitive and not an acute eye; a very pregnant source of mistake. For experience shows that an eye good for faint star and satellite work is constitutionally defective for planetary detail and vice versa; a fact dependent apparently upon the size of the retinal rods and cones.[1]

Lastly, I may remark parenthetically that Professor Newcomb's theory leads him with his supposed fringe for the canals (p. 15, bottom) to a real width much smaller than the visible one, so that he actually strengthens unwittingly the argument for their fineness. This brings us back to what is visible in a telescope.

To begin with, the "canals" of *Mars*, seen through the telescope with good definition at Flagstaff, are not diffuse streaks but narrow definite lines. Now, as Professor Newcomb with justice and good judgment remarks of these very observations: "what is seen by a single practiced observer under the most favorable conditions affords evidence which completely outweighs those of less-favored observers." Indeed it is evident that what is seen by a trained observer under good definition cannot be disputed by failure to see by others; *a fortiori* when all the observers at a station chosen for just this purpose concur, which is the case here. Now the observations at Flagstaff are perfectly definite on the point. In fact the Martian canals actually appear darker and more pronounced than do the writer's drawings of them when telescopically viewed to subtend the same angle.

Next we come to the experimental tests also made at Flagstaff through the telescope upon lines ruled on paper with ink, set up at a distance of 585 feet. The lines were of various character: straight and uniform; linked by having some parts thicker than others; broken, the breaks being of different dimensions. The lines were prepared by Mr. Williams at this observatory, and their configuration and special character were unknown to the observers.

The distance from the 4-inch Clark achromatic to the board upon which the paper was tacked was 178,000 mm. One-tenth of a millimeter on the paper subtended, therefore, $0.''116$ to the naked eye, which with a power of 28 on the telescope became $3.''24$ and with one of 37, $4.''29$.

At opposition this year *Mars* was roughly 39,000,000 miles away.

[1] See Webb, Williams, Lowell, on the subject.

One mile at that distance seen with a power of 391, the one commonly used on the 24-inch at this opposition, subtended therefore 2″.06. Consequently 0.1 mm in the experiment viewed with a power of 28 = 1.57 miles on *Mars;* with a power of 37, it = 2.1 miles. Now, in the first place, the linked lines were instantly seen to be of irregular width and the number of irregularities counted correctly with a power of 37 by both Mr. Lampland and me when the difference between the thicker and thinner portions was only 0.15 mm. Now with the eye-piece this equaled three miles on *Mars;* the width of the links in the case being eight miles and five miles. Thus the difference between a canal of eight miles and one of five was discernible.

In the next place a break in the lines of as little as 0.75 mm was visible; while one of 0.6 mm was so at times, though at others the line showed continuous. Seventy-five hundreths of a milimeter is a quantity corresponding to twelve miles (19 km) on *Mars;* six-tenths of a millimeter to nine and one-half miles (15 km).

The narrowest line drawn, which was by no means at the limit of vision, was 0.12 mm wide and was easily visible with a power of 28. This equaled less than two miles (3 km) on *Mars.* Mr. Lampland's observations substantially agreed with mine in these particulars.

The telescopic verdict at Flagstaff, then, as to the detection of irregularities and breaks in seemingly regular lines is:

1. A difference in thickness which corresponded in angular dimension to three miles on *Mars* was perceptible telescopically;
2. A break, analogously, exceeding eighteen miles (29 km) on *Mars* was discernible;
3. A line of a width of less than two miles (3 km) on *Mars* was easily visible.

We are therefore confronted with the following alternatives: either the "canals" of *Mars* are as they seem, narrow straight lines; or they are syntheses of small markings which show the following surprising characteristics: the pieces never differ by more than three miles in width; secondly, are never farther apart than eighteen miles (29 km); thirdly, are arranged in a perfect row for twenty-five hundred miles (4000 km), more or less, and lastly, exhibit this remarkable connection not in one but in every instance, to the number of over four hundred, in which they occur. If we double these figures, even,

to allow for greater magnification in the telescope, the oddity is not substantially changed. Anyone acquainted or even unacquainted with the laws of probability will have no doubt in coming to a decision as to which alternative is the more probable.

LOWELL OBSERVATORY, FLAGSTAFF, ARIZ.
August 5, 1907

NOTE ON THE PRECEDING PAPER

By SIMON NEWCOMB

While it is a pleasure to appreciate the weight of Professor Lowell's argument, I cannot concede that either of the factors he mentions has been omitted by me in a way to change the character of my results. As to the second of the omissions, my results are based on light between λ 5614 and λ 5894, a region in which the light-intensity is nearly uniform, and not on the fainter red and violet light, the slight effect of which is rightly emphasized. As to the other point, Mr. Lowell seems to overlook the wide difference between the shading off of the dispersed light around the sharpest image of a luminous point, and the diffusion by aberration of the image of a black point on a bright background. In the last case, the image does not consist of a black central point rapidly shading off as the inverse square of the distance from the center, but of an ill-defined half-tone, shading off much less rapidly. This is true in a yet greater degree of the image of a dark line on a bright background, which is the case of the Martian canals.

Mr. Lowell's citations from Mr. H. Dennis Taylor and his own useful telescopic observations of artificial dark lines on a light background, afford excellent illustrations of the process of visual inference described in my paper (pp. 8, 9). To apply them it is only necessary to compute the actual breadth of the images of the lines on the observer's retina, and compare them with what the observer "sees" or thinks he sees.

One word to correct a possible misapprehension of the bearing of my argument. So far as it goes, the canals of *Mars* might be fine lines of inky blackness. It only seeks to show that there is an indefinite number of other features which an observer may train himself into interpreting as fine dark lines, and that the actualities on *Mars* may therefore differ widely from the observer's optical inferences.

I shall be glad if Mr. Lowell will either distinctly accept, or revise if necessary, my computation of the area of the image of the entire canal system on the retina of the eye, and investigate the optical effects arising from it.

REPLY TO PROFESSOR NEWCOMB'S NOTE

By PERCIVAL LOWELL

Professor Newcomb's note has been sent me with the question as to whether I would reply to it. It need only be said:

First, that it is precisely to light between $\lambda = 5614$ and $\lambda = 5894$ that Mr. Taylor's experiments referred.

Second, that the general mathematical treatment is the same for a bright line on a dark area, or a dark line on a bright one, as only the light-disturbance can be integrated in either case, the former being slightly widened, the latter slightly narrowed in consequence; and I particularly showed, i. e., by a star disk and by the shadows of *Jupiter's* satellites, that in both cases no haziness was produced perceptible to the eye.

Third, instead of its being true that Mr. Taylor's and our experiments afford excellent illustrations of the process of visual inference described by Professor Newcomb, the exact reverse is the case, as shown in my paper and as Professor Newcomb will find when he shall subject his a priori supposition to actual experimental tests with instruments.

Professor Newcomb's request for a revision of his computation as to the area of the image of the entire canal system on the retina of the eye I am very glad to comply with, though it only brings out more strikingly the linearity of the canals. From their zonal numbers and breadth, which is too small to disclose any sensible width and can be got only by comparison of intensity with the micrometer thread and by other experiments, giving fifteen miles as the maximum width of the average canal, their area comes out approximately $\frac{1}{10}$ of the surface of the planet. As to the retinal area, it is probable that when a single cone is struck it responds *in toto* and indivisibly to the stimulus, gauging size solely by intensity. With a disk of 23″ and a power of 393, the *minimum divisibile* on *Mars* is 28 miles (45 km), i. e., a single cone corresponds to this space. Therefore, as each canal shows no perceptible breadth, it wakes a single line of cones only and therefore cannot possibly show perceptible shading at its sides, while the retinal area, if such we may call it, is twice the above value. If the cone does not respond *in toto* the area diminishes to the above as its limit.

THE WEAKENED AND OBLITERATED LINES IN THE SUN-SPOT SPECTRUM

By G. NAGARAJA

Of the diverse features in the spectra of sun-spots the widened lines alone have received the greatest attention from observers. They are no doubt the most conspicuous. Several lists of them have been published, but so far some other peculiarities of the spot spectrum are only just beginning to receive attention. Especially is this the case with the weakened and obliterated lines. They have certainly been long recognized as characteristic of spots, but their number and character have yet to be properly estimated. Dr. W. M. Mitchell in an exhaustive catalogue of spot-affected lines between *a* and F has recorded for a total of 680 such lines about 50 as enfeebled.[1] In a later list and in connection with an allied phenomenon in spots, "the reversed lines," he has increased their number.[2] Messrs. Hale and Adams in their photographic observations of the spectra of spots have included but 26 weakened lines in a catalogue of about 345 which are affected in spots.[3] In another paper[4] dealing with the temperature of spots they have taken into account only 32 enfeebled lines for the whole region from λ 4060 to λ 5860. Professor Fowler[5] has considered about 30 weakened lines which he has found to belong to the high levels of the chromosphere. Some visual observations of mine on several large spots made me suspect that the weakened lines in spots were far more numerous than has been previously recorded. I have recently been enabled through the kindness of Mr. Evershed to obtain spectrum photographs of the large spots of May and June last. He found a concave parabolic grating belonging to Professor Michie Smith to be very good and mounted it for me in the Rowland spectrograph instrument of this observatory. This grating has a ruled surface of 1.8 inches (4.57 cm) with 15 028 lines to the inch (2.54 cm) and its focal length for parallel rays is 10 feet (3.05 meters), the radius of curvature being 20 feet (6.10 meters). By the use of a collimating lens the plates are actually exposed at a distance of about 12 feet (3.66 meters)

[1] *Astrophysical Journal*, 22, 4, 1905.

[2] *Ibid.*, 24, 78, 1906.

[3] *Ibid.*, 23, 11, 1906.

[4] *Ibid.*, 24, 185, 1906.

[5] *Monthly Notices*, 66, 361, 1906.

from the grating. Astigmatism is avoided by placing the camera tube normal to the grating and using approximately parallel light. A solar image of about 4 inches (10.16 cm) diameter is formed on the slit by a Grubb lens of 6 inches (15.24 cm) aperture and 40 feet (12.20 meters) focus fed by a siderostat. A sliding shutter with V-shaped aperture is arranged on the slit-plate, which enables the length of the slit to be varied between wide limits, thus allowing different lengths of exposure to be made for spot and sun. The definition of the grating is fine and the resolution is very good in the third order, which on one side is particularly bright.

Several excellent photographs were obtained of the region of spectrum between D and F. Rather long exposures were needed, notwithstanding the brightness of the grating, on account of the small angular aperture of the 40-foot lens; usually between 3 and 4 minutes were required for a spot, and 30 seconds for the adjacent photosphere,[1] this ratio giving approximately equal densities to the two spectra under the atmospheric conditions prevailing here. The linear dispersion is about 1.45 tenth-meters per millimeter and the definition is good enough to show the close doubles b_3 and 5316.8 distinctly resolved on the negatives.

An examination of the plates indicates quite clearly that the previous estimates of the number of weakened lines in sun-spots have been too low. I have carefully gone over the portion D to F on the photographs and have catalogued (leaving all doubtful cases) clear instances of 167 lines which are either thinned, weakened, or obliterated in spots. That is about half as many as the widened lines in the same region. As to the general character of these enfeebled lines, they are all of intensities in the sun ranging from 5 to 000 on Rowland's scale. The enfeeblement is generally through one or two intensities on the same scale. The greatest has been through 4, observed in the case of a few lines belonging to iron. I have included in the table at the end only those that varied through one or more units. Half or intermediate intensities might have been used and would have added more to the list, but I was afraid it would involve doubtful cases. One chief

[1] A small direct-vision prism is generally used in front of the slit to separate the different orders, and this, or the use of absorbing solutions, further reduces the intensity of the spectrum.

characteristic of the enfeeblement is that it is solely a feature of the umbrae of spots. The weakened lines differ in this respect from the reinforced lines, which, except in the case of spot-bands, generally encroach into the penumbra. We could also easily recognize in the photographs certain types among the enfeebled lines. Some are merely thinned, others are weakened and appear a few shades less dark in the spot than in the sun. Among the latter several seem diffusedly to extend to either red or violet side and in rare cases on both sides. One class of lines, generally of small intensity in the sun, are wholly obliterated in the spots.

The first question with regard to these lines will be as to what extent they are characteristic of spots, whether they are a permanent feature or occur only in single spots. There is, however, nothing to warrant the latter view except perhaps the meager and scattered character of previous observations. It may be stated in this connection that visual observations of the weakened lines are by no means easy. Very fine weather and spots with large umbrae seem to be essential. They fail to catch the eye as readily as the widened lines. That is probably one explanation why the observations are so few. It may be plausibly suggested, however, that this phenomenon may be characteristic of some active spots only. But I have observed them in some quiet ones which showed no sort of disturbance as is usually indicated by the behavior of the hydrogen lines. The spots of May and June from the spectrum photographs of which the accompanying catalogue has been prepared did not appear to belong to the class of active spots. At least at the time when the plates were exposed there was no disturbance going on.

But if it be asked whether the same lines are affected in all spots or in the same manner it is certainly too early to attempt a definite answer to the question. Dr. Mitchell has expressed the opinion that they vary and that he has found more weakened lines in 1906 than in 1905.[1] My own impression, however, is that there is not much variation. I have compared the different observations for the region D to F. Of the 26 lines contained in Hale and Adams' catalogue, 22 are in my list. It was quite a surprise to me that even the estimates of the degree of enfeeblement were either the same or very close in

[1] *Astrophysical Journal*, 24, 78, 1906.

TABLE I

Table of Weakened and Obliterated Lines in Sun-Spot Spectrum Photographed at Kodaikanal in May and June 1907 Solar Latitude of Spot, 12 and 13 South

Wave-Length	Origin	Intensity in Sun	Intensity in Spot	Remarks
4874.196	*Ti*	0	00	p-*Ti*(Lockyer) almost obliterated in Hale's map
4874.926	*Ni*	0	00	
4875.215	—	0	00	
4876.586	*Cr*	1	0	p-*Cr* (Lockyer); Mitchell gives maximum weakening
4893.997	—	00	—	Obliterated; see Note 1
4894.743	—	00	—	Obliterated
4900.301	*Y*	2	1	p-*Y* (Lockyer)
4912.666	*Cr*	000	—	p-*Cr* (Lockyer). Obliterated
4914.150	—	2	1	Weakens and also seems to thin on the red side
4916.426	—	000	—	Obliterated
4918.190	*Fe*	1	0	Weakens and also thins on violet side
4924.107	*Fe*	5	3	p-*Fe* (Lockyer). Chromospheric line
4925.450	*Fe*	00	000	Mitchell gives a line at λ 4925.75, probably this
4936.015	*Ni*	2	1	
4937.245	—	00	—	Obliterated
4937.524	*Ni?*	3	2	Thinned
4945.622	*Ni*	1	00	
4945.814	*Fe*	1	0	
4946.215	*Ni*	0	00	Almost obliterated in Hale's map
4947.778	—	00	000	
4965.351	*Ni*	0	—	Obliterated
4974.431	—	000	—	Obliterated; a broad dark spot-band falls over the place
4984.297	*Ni*	2	1	
4985.432	*Fe*	3	2	
4986.403	*Fe*	1	0	
4987.088	—	00	—	Obliterated
4995.586	—	00 }	—	Obliterated; a broad spot-band falls over the lines and extends to the violet side
.835	—	00 }		
4996.558	—	000	—	Obliterated
4997.024	*Ni*	1	0	
4998.408	*Ni*	1	0	Thinned; Mitchell gives maximum intensity
4999.207	*Fe*	0	00	Mitchell gives a line at λ 4999.69, probably this
5008.825	—	000	—	Obliterated; spot-band falls over the place. Only weakened in Hale's map
5010.396	—	00	—	Obliterated
5013.871	—	0	00	
5014.100	—	00	—	Obliterated
5022.414	*Fe*	3	2	Weakened only slightly in Hale's map; see Note 2
5023.372	*Fe*	0	00	Hale's map shows a spot-band over the place which is not seen in my photographs
5027.937	*Fe*	1	00	Mitchell gives this line
5048.242	*Ni*	0 }	000	
.409	—	00 }		
5052.338	—	0	—	Obliterated
5057.665	*Fe,Ni*	0	00	A bright band falls over the line
5072.479	*Ti*	0	—	p-*Ti* (Lockyer). Obliterated
5082.526	*Ni*	2	0	Hale and Mitchell give in their list, but is not clearly shown in Hale's map

TABLE I—*Continued*

Wave-Length	Origin	Intensity in Sun	Intensity in Spot	Remarks
5084.279	*Ni*	3	2	A bright line falls just to the red side and thins the line on that side
5086.422	—	00	—	Obliterated; a bright band falls over the line
5087.601	*Y?*	1	00	Chromospheric line
5089.134	*Ni*	0	00	
5094.594	*Ni*	1	0	
5103.142	*Ni*	1	0	Thinned
5115.566	*Ni*	2	1	A bright line falls just to the red side
5115.961	*Fe*	0	00	
5118.112	*Mn*	00	000	Thinned; bright bands fall on both sides of the line
5119.292	—	00	—	Obliterated
5121.732	*Ni*	0 }	0	Hale and Mitchell give the line
.825	*Fe*	2 }		
5129.805	*Fe*	1	—	Obliterated; a broad dark band falls over the region. See Note 3
5132.843	—	00	—	Obliterated; Hale gives the line
5140.992	—	00	—	Obliterated
5147.273	—	000	—	Obliterated
5154.579	—	000	—	Obliterated; see Note 4
5158.152	—	00	000	
5159.231	*Fe*	2	1	Hale and Mitchell give the line; see Note 5
5164.724	*Fe?*	1	0	Hale and Mitchell give the line
5165.080	*C*, —	000	—	Thins on the red side
5170.937	*Fe*	0	—	There is a close widened line on the red side
5176.737	*Ni*	1	000	A bright band on violet side encroaches into the line and thins it
5178.970	—	00	—	
5186.073	*Ti*	2	1	p-*Ti* (Lockyer). Weakened and diffusedly extending to violet side
5188.079	*Fe*	1	0	Weakened and diffusedly extending to red side
5197.332	*Ni*,*Mn*	00	000	
5197.743	—	2	000	p-*Fe* (Fowler). Chromospheric line
5198.108	—	0	00	
5211.700	*Fe*	00	000	Thinned
5213.515	—	000	—	Obliterated; Rowland's intensity for the line is too small
5215.737	—	000	—	Obliterated
5218.085	*Fe*	0 }	1	
.369	*Fe*	1 }		
5220.358	*Ni*	0	00	
5226.707	*Ti*	2	1	p-*Ti*. Thinned; chromospheric line
5234.791	—	2	0	p-*Fe* (Fowler). Chromospheric line
5236.373	—	0	00	
5237.497	*Cr*	1	00	p-*Cr*. Weakened and diffusedly extending both ways
5239.992	—	1	00	Weakened and diffusedly extending to red side
5257.100	*Sr?*	00	000	
5264.976	—	0	00	Hale gives the line
5271.464	—	00	—	Obliterated
5275.148	—	0	—	Obliterated
5280.239	*Cr*	00	—	p-*Cr*. Obliterated
5284.281	*Ti*	1	00	Mitchell gives the line; thinned and weakened

TABLE I—*Continued*

Wave Length	Origin	Intensity in Sun	Intensity in Spot	Remarks
5284.787	—	00	—	Obliterated
5292.762	*Fe*	0	00	Weakened and diffusedly extending to violet side
5293.211	Awv ?	00	—	Obliterated; Mitchell gives this as a chromospheric line
5294.134	*Fe*	0	00 ?	
5294.726	—	00	000	Thinned
5306.040	*Cr ?*	0	00	5306.3 p-*Cr* (Lockyer)
5316.790	*Fe*	4	3	p-*Fe*. Hale and Fowler give the line; chromospheric line
5317.724	—	00	—	Obliterated
5325.738	—	2	1	Fowler gives the line; chromospheric line.
5335.050	*Cr*	1	0	p-*Cr* (Hale). 5335.5 p-*Cr* (Lockyer)
5336.974	*Ti*	4	3	p-*Ti* (Lockyer)
5337.910	—	0	00	Hale gives the line
5342.890	*Co*	1	0	
5359.389	*Co*	00	—	Obliterated
5363.058	—	3	2	p-*Fe* (Fowler). Chromospheric line
5377.028	*Fe*	0	00	Thinned
5381.221	*Ti*	2	1	p-*Ti* (Lockyer). Rowland gives this as belonging to *Fe*
5409.339	*Fe*	2	1	The line is thinned on red side but extends far into the violet side in spot
5411.428	*Ni*	1	0	Thinned
5414.279	—	0	—	Obliterated
5425.464	—	1	0	Hale and Mitchell give the line
5478.668	*Cr*	0	000	p-*Cr*
5494.063	—	0	—	Obliterated
5502.297	—	0	00	
5503.286	*Fe*	1	0	Weakened and thinned
5508.840	*Cr*	0	—	p-*Cr*. Obliterated
5510.229	*Ni*	1	0	
5519.797	*Fe*	0	00	Thinned
5527.033	*Sc*	3	2	p-*Sc* (Fowler)
5532.202	—	00	—	Obliterated
5532.968	—	1	0	
5535.061	*Fe*	2	1	
5539.507	*Fe*	0	—	Obliterated
5560.434	*Fe*	2	1	
5561.464	—	00	—	Obliterated; Hale's map does not show it
5620.715	*Fe*	00	000	
5625.541	*Ni*	0	000	Thinned
5625.904	—	00	—	
5636.925	*Fe*	0	000	
5637.339	*Ni*	1	0	
5637.632	*Fe*	1	0	
5640.538	—	0	—	
5641.206	—	1	0	
5645.830	*Si*	1	000	Hale and Mitchell give the line
5649.898	*Fe,Ni*	0	00	
5650.209	*Fe*	1	00	
5650.911	*Fe*	1	0	
5651.691	*Fe*	0	000	
5659.817	*Fe*	0	000	

TABLE I—*Continued*

Wave-Length	Origin	Intensity in Sun	Intensity in Spot	Remarks
5665.775	*Si*	1	00	
5666.899	—	0	00	
5669.258	—	1	0	Hale and Mitchell give the line
5669.962	*Ni*	0	—	
70.163	—	0		
5682.427	—	2	0	
5684.710	*Si*	3	0	Hale and Mitchell give the line
5686.757	*Fe*	3	2	
5690.646	*Si*	3	2	Hale and Mitchell give the line
5701.323	*Si*	1	000	Hale and Mitchell give the line
5704.960	A	0	00	
5708.622	*Si*	3	1	Hale and Mitchell give the line; diffusedly extends to red side
5714.380	*Fe*	0	—	Obliterated
5731.984	*Fe*	4	3	Mitchell gives the line; not shown in Hale's map
5752.254	*Fe*	4	3	Weakened and diffusedly extending both ways
5753.860	*Cr*	1	00	
5757.037	*Fe*	2	1	
5772.364	*Si*	3	1	Hale gives the line; diffusedly extending to red
5784.879	*Fe*	1	—	Obliterated
5785.498	*Fe*	3	1	
5793.292	—	3	2	Not shown in Hale's map
5798.077	—	3	1	Hale and Mitchell give the line; but not shown in Hale's map
5804.681	*Fe*	0	—	Obliterated; Mitchell gives the line; not shown in Hale's map
5831.821	*Ni*	1	0	
5835.645	—	00	000	
5855.300	*Fe*	1	0	
5856.312	*Fe*	2	1	

[1] A faintly dark shading is seen just to the violet side of where this line ought to be in the spot.

[2] Hale and Adams give the line as decreased in weak arc.

[3] There is a p-*Ti* line close to the line at λ 5129.32.

[4] A bright line appears in the spot in place of the Fraunhofer line over a dark band that falls over the region. There is p-*Ti* close at λ 5154.24.

[5] A diffused dark band extends to red side from the line.

all the 22 cases. As to the remaining 4 lines which I had not included, I found they had all been given by Hale and Adams only a weakening of half an intensity on the Rowland scale. They had therefore been excluded from my table. Probably this close agreement between different observers could have been possible only by the photographic method in the study of the sun-spot spectrum. Fowler's method of estimating intensities should also be responsible for some of this accuracy. There is, however, less agreement between Mitchell's observations and mine, and I have noted in the table all those found in the former's

TABLE II (SUMMARY OF TABLE I)

Elements	Number of Weakened Lines in Spots	Number of Widened Lines in Spots	Enhanced Lines Weakened in Spots	Enhanced Lines Not Weakened in Spots	Remarks
Unknown....	59	94	—	—	
Fe..........	48	50	5	2	
Ni..........	26	7	—	—	
Si..........	7	—	—	—	
Ti..........	7	48	6	1	
Cr..........	9	42	8	—	(1)
Co..........	2	5	—	—	
Y..........	2	—	1	—	
Sc..........	1	—	1	—	
Mn..........	1	13	—	—	

Rowland's identifications *Ni, Mn, Sr?, C*, —, *A*, *A*(*wv*) have each one weakened line in the region.

[1] There is one *Cr* line at λ 5753.860 about which it is not known whether it is enhanced or not, as Lockyer's tables have not been extended to that wave-length.

TABLE III (CHROMOSPHERIC LINES)

Wave-Length	Origin	Observers[2]	Level of Chromosphere	Weak-ened or not	Remarks
4861.527 (F)[1]	*H*		High level		
4883.869	*Yt* (earth)	N.	Low level	No	
4900.301	*Y?*	Y. N.	Low level	Yes	p-*Y* (Lockyer)
4921.963	*La-Ti*	Y. N.	High level	No	
4924.107	*Fe*	Y. N.	High level	Yes	p-*Fe* (Lockyer)
4934.214	*Ba*	Y. N.	High level	No	
.277					
4993.699 .864	— *Fe*	N.	Low level	No	
5015.9	*He*	Y. N.	High level	No	
5018.629	*Fe*	Y. N.	High level	No	p-*Fe* (Lockyer)
5087.601	*Y?*	N.	Low level	Yes	
5167.497 .678 b_4	*Mg* *Fe*	Y. N.	Low level	No	
5169.069 .220 b_3	*Fe*	Y. N.	High level	No	p-*Fe* (Lockyer)
5172.856 b_2	*Mg*	Y. N.	High level	No	
5183.791 b_1	*Mg*	Y. N.	High level	No	
5186.073	*Ti*	F.	Low level	Yes	p-*Ti* (Lockyer)
5188.863	*Ti*	Y. N.	Low level	No	p-*Ti* (Lockyer)
5197.743	*Fe*	Y. N. F.	High level	Yes	p-*Fe* (Fowler)
5200.355 .590	*Cr* *Va*	N.	Low level	No	
5204.1	—	N.	Low level	No	
5205.897 06.265	*Y* *Cr-Ti*	N.	Low level	No	
5208.596 .776	*Cr* *Fe*	N.	Low level	No	
5226.707	*Ti*	Y. N. F.	Low level	Yes	p-*Ti* (Lockyer)

TABLE III—*Continued*

Wave Lengths	Origin	Observers[2]	Level of Chromosphere	Weakened or not	Remarks
5234·791	*Fe*	Y. N. F.	High level	Yes	p-*Fe* (Fowler)
5237·497	*Cr*	F.	High level	Yes	p-*Cr* (Lockyer)
5264·976	—	F.	High level	Yes	
5269·723 E_2	*Fe*	Y. N.	Low level	No	
5276.169	*Fe?*	Y. N.	High level	No	
5284.281	*Ti*	Y. F. N.	High level	Yes	
5316.790	*Fe*	Y. N. F	High level	Yes	p-*Fe* (Lockyer)
5325·738	—	N. F.	High level	Yes	
5328.696 }	*Fe*	N.	Low level	No	
·747 }					
5336·974	*Ti*	F.	High level	Yes	p-*Ti* (Lockyer)
5363·058	*Fe*	Y. N. F.	High level	Yes	p-*Fe* (Fowler)
5371·656	*Cr?* }	N.	Low level	No	
·734	*Fe* }				
5381.221	*Ti*		High level	Yes	p-*Ti* (Lockyer)
5397·344	*Fe*	N.	Low level	No	
5405.989	*Fe*	N.	Low level	No	
5425·464	—	H. M. F. N.	High level	Yes	
5429·991	*Fe*	N.	Low level	No	
5434·740	*Fe*	N.	Low level	No	
5447·130	*Fe*	N.	Low level	No	
5455·671	*Fe?* }	N.	Low level	No	
.834	*Fe* }				
5527·033	*Sc*	N. F.	High level	Yes	p-*Sc* (Fowler)
5535·061	*Fe*	Y. N. F.	High level	Yes	

[1] Wings of $H\beta$ obliterated in spot which therefore appear narrower than on photosphere. $H\delta$ on another plate taken about the same time is very much weakened in spot.

[2] Y refers to Young, F to Fowler, M to Mitchell, H to Hale, and N to the present writer.

TABLE IV (SUMMARY OF TABLE III)

CHROMOSPHERIC LINES—44

Weakened in Spots 18				Not Weakened in Spots 26			
High Level 14		Low Level 4		High Level 9		Low Level 17	
Enhanced 9	Not Enhanced 2	Enhanced 3	Not Enhanced 1	Enhanced 2	Not Enhanced 7	Enhanced 1	Not Enhanced 16
Fe—5	*Fe*—1	*Ti*—2	*Y*—1	*Fe*—2	*Mg*—2	*Ti*—1	*Fe*—12
Ti—2	*Ti*—1	*Y*—1			*La, Ti* 1		*Cr*—3
Cr—1					*Fe?* 1		*Mg*—1
Sc—1					*Ba*—1		
					H—1		
Unknown 3					*He*—1		

catalogue. Nearly all the lines given by Fowler are in my list and are also noted. But what bears most on the point is that almost

all the lines in my catalogue are distinctly enfeebled in the reproductions of the Mount Wilson photographs of spot spectra which we recently received from Professor Hale. Of the 167 lines in my list only 7 are not shown in the reproductions. Of these 4 are of very low intensity in the sun and are completely obliterated in my photographs. It would thus appear that Hale and Adams in the preliminary study of their photographs did not particularly look for this phenomenon but simply recorded those that thrust themselves on their notice when they were examining the plates for the widened lines. We may then as a result of this close agreement conclude that between the time of the Mount Wilson photographs, which were taken probably some time during the latter part of 1905, and the middle of the present year, there has not been any noticeable variation of the weakened lines in the spectra of sun-spots.

I shall next consider some points of interest disclosed in the catalogue. In the summary (Table II) I give a list of the elements concerned, with the number of weakened lines in each case. And as it may be useful to compare the behavior of the same elements in the production of the widened lines, I have given the latter as well. These are extracted from the tables of Hale and Adams[1] and relate to very nearly the same reigon as I have dealt with. In the light of the connection that has been recently traced between the enfeebled lines in spots and the enhanced lines of some of the elements I have, along with noting them in the larger list, summarized them also, in Table II.

Comparing the weakened with the strengthened lines in spots we find that a large proportion in both cases are of unknown origin. Then comes iron, contributing nearly an equal number to either phenomenon. There are about 250 other iron lines in the same region which are probably unaffected in spots. We can only gather that as between the two cases iron does not seem to have any particular partiality. But not so some of the other elements. Most of the titanium and chromium lines are widened, while the nickel and silicon lines exhibit a similar partiality for weakening. The last, it should be noted, has all its lines in the region enfeebled.

With regard to the enhanced lines that are represented in the list, I am indebted to Mr. Evershed for the identification of most of them.

[1] *Astrophysical Journal*, 23, 28, 1906.

Reference has already been made to the 32 weakened lines which Hale has considered in his paper on the temperature of spots and of which he has found 29 to be spark lines. There is, however, nothing like this proportion disclosed in my table and the enhanced lines form by no means a large fraction of the total number. But it is to be remarked that Hale has included in his inquiry the more refrangible part of the spectrum, which is especially rich in enhanced lines, and also that complete tables are not available for the other regions. Still, within the portion I have considered, there are about 40 spark lines belonging to iron, titanium, and chromium which are found in Lockyer's tables, and 4 more which have been recently noted by Fowler to be enhanced. Of these 19 are found in the catalogue, and 10 are too little affected to be included in it, but still they appear to be slightly weakened.[1] In the case of the rest, most of them are only of small intensity in the spark and a few are too faint to be seen either in the sun or in the spot. There are, however, some 5 instances of enhanced lines of tolerable intensity in the spark not being affected at all in the spot. They are λ 5169.07 and λ 5169.22 belonging to iron, λ 5188.87 to titanium, and λ 5502.9 and λ 5621.7 to chromium. Thus, though it cannot be said that most of the weakened lines in spots are spark lines, we see, however, that a great majority of the latter are weakened in spots. It is also to be noticed that almost all the titanium and chromium lines weakened in spots are spark lines of those elements. The only exception is that of λ 5284.281, which Rowland has identified as belonging to titanium, but which is not found in Lockyer's table of enhanced lines. In the case of iron, while most of the spark lines in the region dealt with are weakened, yet a large majority of the weakened lines of this element are not spark lines, or have not as yet been identified as such. We have already seen that iron was concerned almost equally with producing both the widened and weakened lines, while titanium and chromium contribute mostly to the widened lines. It is then significant that when some lines of the two last elements suffer weakening in spots they should be almost all enhanced lines. Messrs. Hale, Adams, and Gale have from the laboratory experiments found that the spark lines of iron,

[1] Two more enhanced lines are in the list, one of which has been assigned by Fowler to "proto-scandium" and the other by Lockyer to "proto-yttrium."

titanium, chromium, and vanadium, when passing to a weak arc, are either weakened or obliterated, while the ordinary arc lines are all strengthened.[1] This would lead to the conclusion that the conditions prevailing in spots are analogous to the weak arc, and the Mount Wilson observers have so inferred. It might certainly account for the enhanced lines being weakened in spots. But this view alone cannot explain the presence of so many other weakened lines in spots which have not yet been identified as spark lines.

It may also be interesting to compare the chromospheric lines with those weakened in spots, and Table III has been prepared for that purpose. Only the lines found in the chromosphere between F and D are considered. Most of them have been observed by me and their character as high- or low-level lines determined. To make the table complete as far as possible I have included five other lines from Fowler's list.[2] A summary has also been added (Table IV) from which we gather that only a fraction of the chromospheric lines are weakened in spots. It is brought out further that a good many of the weakened lines belong to the higher levels of the chromosphere; but at the same time the contrary statement cannot be made. This would imply that the cause of weakening is not to be traced to the mere circumstance of these lines being present in the upper chromosphere. An examination of Table IV further discloses that a large majority of the weakened lines in it are also enhanced lines. Leaving out the 3 unknown lines, we find 12 out of the 15 to be spark lines. It has already been noticed that the latter tended generally to weaken in spots. The enfeebling then in the present instance of most of the chromospheric lines that are also weakened in spots may be accounted for solely on the ground of their being enhanced lines at the same time. The predominance of the high-level lines of the chromosphere among the weakened may also be explained by the larger number of the enhanced lines being found in those levels.

In bringing this paper to a close I wish to express my thanks to Mr. Evershed for the valuable help he has given me in the course of its preparation.

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[1] *Astrophysical Journal,* 24, 185, 1906.

[2] *Monthly Notices,* 66, 364, 1906.

A LARGE ERUPTIVE PROMINENCE

By PHILIP FOX

The daily programme of observations with the Rumford spectroheliograph includes a photograph of the prominences around the entire disk of the sun, using the H line. Such a plate taken on May 21, 1907, upon development showed a prominence of unusual size in the south-east quadrant. I returned to the dome immediately to obtain other photographs. The sky was completely overcast with light cirrus clouds, so that the exposures were made under very unfavorable, almost prohibitive, conditions. However, I obtained a total of thirteen photographs the measurements of which give the following results. The position angle was roughly 138°.

Plate Number	No.	G. M. T.	Height	
Σ_s 2280	1	4^h 02^m	228″6	167,800^{km}
2281	2	4 52	259.3	190,300
2282	3	5 01	280.5	205,800
2283	4	5 35	391.6	287,400
	5	5 37	400.0	293,600
2284	6	5 43	431.8	316,900
	7	5 44	370.4	271,900
	8	5 44.5	370.4	271,900
2285	9	5 52	418.0	306,800
	10	5 53	415.9	305,300
	11	5 55	423.3	310,700
2286	12	5 57	410.6	301,400
	13	5 59	412.7	303,000

After exposure No. 6, the clouds so increased in density that the plates are of little worth. The measurements are consequently very unreliable, the fainter, outlying portions being obscured in some instances. They show, however, that the prominence was rapidly disintegrating. Cloudiness during the remainder of the day and for several days following prevented further observation of the region. A spectroheliogram of the disk at G. M. T. 3^h 43^m, using the H line, reveals no other disturbance at this point, and very faintly shows the prominence itself beyond the limb.

The various stages of development of the prominence are well illustrated by the first four exposures, which are reproduced in Plate X.

At first it was firmly rooted to the disk but the connection gradually disappeared, leaving it floating free. It seems plain that the peak of the prominence, as seen in Fig. 1, toppled back to the disk forming the loop of Figs. 2 and 3. Careful comparison of the plates shows that the single spike of Fig. 1 coincides with the center of the loop of Fig. 2, and further that on Fig. 1 there is a very faint arch south of the spike which agrees well in position with the upper arm of the loop. It is probable, however, that the spike bowed to south when the peak fell back. Between Figs. 2 and 3 there is also a decided change. The falling arm of the loop has descended a considerable distance and the force which was to comb the crest of the arch into the long streamers of Fig. 4 was already active. There was a perceptible movement toward the south during the various changes. The two small prominences at position angles 125°9 and 146°9 form good points of reference in comparing the several plates.

It would have been interesting to have some intermediate exposures, as the transformations could then have been followed with greater certainty. The need of obtaining many successive exposures at short intervals of these protean structures is strongly emphasized. It is possible with the Rumford spectroheliograph to make exposures on prominences around the whole disk at intervals of three minutes, and for single prominences the exposures may follow at intervals of less than a minute. For example, on June 8, 1907, I made such a series of exposures upon a group of quiescent prominences at the south limb of the sun, obtaining twenty exposures scattered through an hour. Six of these were made within five minutes. I hope that I may soon have an opportunity to make a series upon a large, rapidly changing prominence.

Yerkes Observatory
September 1907

ORBIT OF THE SPECTROSCOPIC BINARY μ *SAGITTARII*

By NAOZO ICHINOHE

This star ($\alpha = 18^h\ 8^m$, $\delta = -21°5'$; Mag. $=4.1$) was twice observed by Mr. Wright with the Mills spectrograph, on June 19, 1899, and May 30, 1900, and the results show the velocity in the line of sight -75 and -76 km, respectively. Hence the variability of the radial velocity was not detected by him; and Professor Campbell included the star among examples of stars with large radial velocities.[1] In the course of their observations of stars of the *Orion* type, the variability of the velocity was soon discovered[2] by Messrs. Frost and Adams at this observatory, the velocities on April 15 and April 29, 1904, giving a range of variation of 80 km.

μ *Sagittarii* is a multiple star, having five companions whose magnitudes range from 9.2 to 13. Of course the variation of the radial velocity relates only to the principal star. The proper motion of the star was thoroughly investigated by Professor Auwers, as it is contained in his catalogue of the fundamental stars, and it is $0''.027$ in the direction of the position angle $280°.7$. The velocity of the center of inertia of this binary in the line of sight is -7 km per second, as we shall see later. Though we know the proper motion of the star on the celestial sphere as well as the radial velocity, yet we do not know the absolute amount of the motion in space, since the annual parallax of the star is unknown.

The star is included in the *Draper Catalogue* where the spectrum is stated to be of the F type, and the photographic magnitude is 4.23 according to the same catalogue. This is also included in Miss Maury's catalogue and the spectrum is classified under group VI *c*. The following statements will sufficiently describe the characteristic points of the spectrum contained in the region from λ 3900 to λ 4900. The hydrogen lines are all narrow compared with the stars in the foregoing groups, and very well defined. The calcium lines K and H are pretty strong. The helium lines are rather faint; the lines $\lambda\lambda$ 4009,

[1] *Astrophysical Journal*, **13**, 99, 1901.

[2] *Ibid.*, **19**, 351, 1904.

4024, 4121, and 4144 are all feebly impressed, still we can recognize them easily; λ 4388 is very well seen; but the strongest helium lines in this star are λλ 4026 and 4472, which are quite strong and very well measurable. The silicon lines λλ 4128 and 4131 are also quite strong and their intensities are just comparable with those of the strongest lines of helium. We can also clearly see the carbon line λ 4267. The magnesium line λ 4481 is quite distinct. Besides this, the lines which can be measured with accuracy are the pair of silicon lines, $H\gamma$, λλ 4388 and 4472, and also the carbon line. Many faint metallic lines may be recognized, especially those of iron and titanium.

The normal wave-lengths of the lines which have been used for the determinations of the radial velocities are as follows. In this table n denotes how many times the corresponding line has been used for the star, the whole number of the measured plates being 21.

Element	λ	n	Element	λ	n
Ca.K	3933.825	1	*Cr*	4385.144	1
He	4009.417	1	*He*	4388.100	16
He	4024.136	1	*Cr*	4465.519	1
He	4026.370	6	*He*	4471.676	21
$H\delta$	4101.890	13	*Mg*	4481.400	21
V	4111.940	1	*Fe*	4508.455	1
He	4121.016	3	*Fe*	4549.642	2
Si	4128.211	13	*Fe*	4584.018	2
Si	4131.047	13	*Ti*	4590.126	1
He	4143.919	3	*He*	4713.308	2
C ?	4267.301	4	*Ti*	4856.203	1
$H\gamma$	4340.634	21	$H\beta$	4861.527	8

From the table we see that the only lines which were used for all the plates are $H\gamma$, λ 4472 and λ 4481. The lines $H\delta$, λ 4388, two lines of silicon, and a helium line λ 4388 were the ones which are used more frequently than the others.

The following journal of observations for the star requires little explanation. The temperature is that indicated by the thermometer within the outer temperature-case of the spectrograph. In some cases, the readings of the temperature at the beginning and the end of the exposure were not exactly the same; in such cases, their mean was taken in this table. With regard to them, the differences were not so large that the radial velocities determined with such plates would be affected. The column before the last gives the initials

or name of the observers, where F = Frost, A = Adams, and B = Barrett. Here it is understood that Mr. Sullivan guided equally with the observers. The last column gives the estimate of the condition of the sky made by the observer, the first figure representing transparency and the second steadiness. The number 5 is assigned for the very best conditions.

The comparison spectra of iron and titanium were equally impressed by means of the spark at the beginning and the end of the exposures.

μ SAGITTARII

JOURNAL OF OBSERVATIONS

Plate	Date	G. M. T.	Exposure	Slit-Width	Temperature	Observer	Seeing
IB 311....	1904 April 15	20^h 36^m	43^m	0.038 mm	+ 0°.1 C	A	3; 2
323....	April 16	21 36	40	0.038	+ 4.9	A	3; 3
328....	April 29	20 59	42	0.051	+14.8	A	2; 2
335....	April 30	21 04	35	0.038	+16.6	F	3; 1
780....	1906 June 1	20 17	50	0.046	+18.4	F	3; 3
796....	July 9	16 56	74	0.046	+24.8	F	2; 3
805....	July 20	15 21	76	0.046	+27.2	B	2; 2
816 ...	July 27	14 54	60	0.046	+26.6	B	2; 2
819....	Aug. 10	14 55	70	0.046	+24.8	B	2; 3
828....	Aug. 20	14 45	76	0.046	+27.6	F	2; 3
835....	Sept. 5	13 58	72	0.046	+23.2	F	3; 3
841....	Sept. 10	14 15	60	0.046	+25.8	F	3; 3
858....	Sept. 21	14 02	75	0.046	+22.0	B	3; 3
870....	Oct. 1	13 33	76	0.046	+17.0	F	4; 2
882 ...	Oct. 19	12 33	60	0.059	+16.1	F	5; 3
1022....	1907 April 13	22 15	61	0.046	− 0.9	Fox	4; 2
1025....	April 19	21 53	62	0.046	+ 5.8	F	3; 2
1038....	April 22	21 21	110	0.051	+14.2	F	0–2; 2
1045....	April 26	21 56	60	0.051	+ 3.7	F	3; 3
1050....	April 30	21 56	50	0.051	+ 4.2	F	3; 4
1059....	May 10	21 47	50	0.051	+ 5.9	F	3; 3

The measurements as well as their reductions were made according to the same processes as those used by others in this observatory. Among 21 plates, the plates IB 311 and 323 were measured by both Messrs. Frost and Adams. The plate IB 328 was measured by Adams and IB 335 by Frost. The measurements of all the remaining plates were made by myself. The following table shows the results of the measurements, in which the mean values of the two observers for the first two plates were taken. The second column of the table gives

the Julian day, only one decimal place being retained because the accuracy of the radial velocities and the present knowledge of the period make further figures unjustifiable. The third column represents the observed radial velocities reduced to the sun. In this case, the round numbers of km were taken throughout. The next column n shows upon how many lines the result depends.

Plate	Julian Day	v	n	Phase	v_c	$v-v_c$
IB 311....	2416586.9	+46 km	5	139ᵈ1	+44 km	+ 2 km
323....	6587.9	+42	8	140.1	+40	+ 2
328....	6600.9	−34	4	153.1	−33	− 1
335....	6601.9	−34	4	154.1	−36	+ 2
780....	7363.8	−55	11	15.0	−51	− 4
796....	7401.7	−18	8	52.9	−19	+ 1
805....	7412.6	−10	10	63.8	− 9	− 1
816....	7419.6	− 4	6	70.8	− 3	− 1
819....	7433.6	+12	12	84.8	+11	+ 1
828....	7443.6	+32	7	94.8	+23	+ 9
835....	7459.6	+45	8	110.8	+48	− 3
841....	7464.6	+37	11	115.8	+56	−19
858....	7475.6	+65	11	126.8	+65	0
870....	7485.6	+58	7	136.8	+50	+ 8
882....	7503.5	−40	8	154.7	−38	− 2
1022....	7679.9	−21	9	150.9	−21	0
1025....	7685.9	−44	5	156.9	−45	+ 1
1038....	7688.9	−44	3	159.9	−53	+ 9
1045....	7692.9	−42	10	163.9	−60	+18
1050....	7696.9	−63	8	167.7	−63	0
1059....	7706.9	−62	7	178.1	−62	0

The period of the oscillation of velocities was investigated in August of last year by me and it was found that 180 days satisfied all plates used at that time pretty well. For this determination I owe very much to the results by Mr. Wright. This year six more plates were added, which enabled me to correct the period; and finally 180ᵈ2 was taken as the value of the period. The fifth column of the above table was calculated by using this value of the period and J. D. 2414826.0 as the initial epoch. Then the velocities were taken as the ordinates and the phases were taken as the abscissas.

These being plotted upon cross-section paper, a curve was drawn through or near to these points so that the curve became as smooth as possible. Then the elements of the orbit were determined by the method of Lehmann-Filhés.

First of all, the radial velocity of the center of inertia of the system

was determined to be -7 km. Then the following values were obtained for the data necessary for the determination of the elements:

$$A=72\text{ km} \qquad B=57\text{ km}$$
$$Z_1=683 \qquad Z_2=1708$$
$$t_1=148^{d}.3 \qquad t_2=231^{d}.0$$

These give the following elements:

$$U=180^{d}.2$$
$$u_1=96°41'$$
$$\omega=74°43'$$
$$e=0.441$$
$$\mu=2°.00$$
$$\text{or } \log\mu=8.5425$$
$$a\sin i=143{,}500{,}000\text{ km}$$
$$T=144^{d}.4$$
$$\text{or } T=2414968^{d}.4$$
$$m+m'=\frac{3.5\odot}{\sin^3 i}$$

If we represent a sin i in terms of the mean distance of the earth from the sun, it will be 0.965. Therefore, a is quite comparable with that of the earth's orbit unless the inclination be quite small. I calculated the following, assuming various values of i:

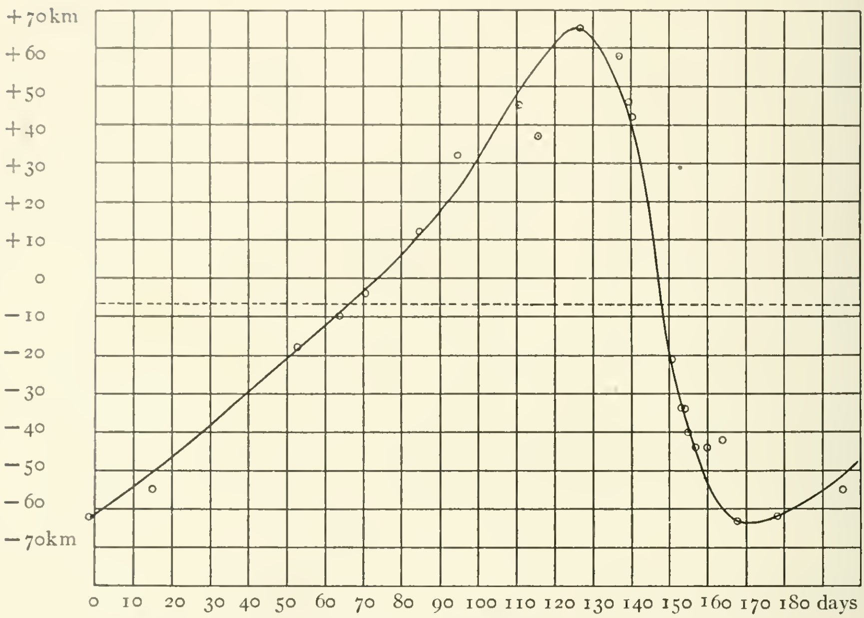
i	a	Astron. units
30°	287,000,000 km	=1.930
45	202,900,000	=1.365
60	165,700,000	=1.114
75	148,600,000	=0.999
90	143,500,000	=0.965

With regard to the ratio of the masses of the both components I cannot say more than the above with certainty.

Next, using the above set of elements, I have calculated an ephemeris in order to see how closely these elements will represent the observations and the curve in the accompanying figure was drawn with these computed values. The centers of the small circles show the observed values.

The computed values were given in the column before the last in the above table. The deviations of the observations from the computations gives the values of the last column. The examination

of $v - v_c$ shows that the orbit represents the observations pretty well except for the two plates IB 841 and 1045. The former is a very good plate; still it gave too low a velocity; but when I consulted the original sheets of measurements, I found that the separate results for the different lines were not satisfactorily coincident. The latter is not a good plate; the comparison lines and star lines were very fuzzy.



COMPUTED VELOCITY–CURVE FOR *μ Sagittarii,* WITH OBSERVED POINTS

For this reason I measured these two plates again and found the following results:

IB	841	+43 km
	1045	−42 km

As stated already, the two plates by Wright played an important rôle in the determination of the period of the star, but when the discussion was made, we found that the minimum velocity of the star is −63 km instead of −76 km; and the residuals become −12 and −14 km respectively. These are too large for accidental errors. Undoubtedly Wright's plates were obtained with the Mills three-prism spectrograph.

Our result rests entirely on Bruce one-prism spectrograms. According to the long experience, there is no appreciable systematic difference between the results by the Mills three-prism instrument and those by Bruce three-prism instrument. The question then is whether there is any systematic error between these results from the one-prism and three-prism plates, or whether the above residuals can be considered as merely accidental errors. At present my data are not sufficient to decide which assumption is preferable. It should be stated, however, that measures of control spectrograms of the Moon (four in number, made several years ago) by Mr. Adams and Mr. Frost indicate no systematic differences between three-prism and one-prism plates.

It is with great pleasure that I acknowledge my indebtedness to Professor Frost who suggested that I investigate the star and was interested in the work while I was carrying it on.

Yerkes Observatory
August 1907

A GRAPHIC DETERMINATION OF THE ELEMENTS OF THE ORBITS OF SPECTROSCOPIC BINARIES

By KURT LAVES

So far there does not seem to have been offered a purely geometric proceeding by which the elements of the orbit of a spectroscopic binary can be determined. The two methods of Lehmann-Filhés[1] and Schwarzschild[2] combine certain geometric features with an analytic mode of solution.

Now it is evident from the geometric properties of the hodograph of conic sections described under Newton's law of attraction, that it will permit a very direct derivation of the formula for $\frac{dz}{dt}$ in terms of K, e, u, ω, and i as it is used in this work. Since the majority of the astrophysicists employ the original notation of Lehmann-Filhés, it seems best to adopt it in what follows. K, in our way of interpretation, is simply the radius of the hodographic circle. Since we are unable to determine the inclination i between the orbital plane and the tangential plane, we may as well assume $i=90°$; i. e., suppose that the line of sight is constantly contained in the plane of motion. This permits us to avoid the elliptic projection of the hodographic circle on the plane of sight which passes through the line of nodes. We shall see that after the velocity of the center of gravity γ and the period U has been found from the curve of oscillation (to use Hartmann's very appropriate abbreviated term), we determine from A and B the radius K of the hodograph and $\gamma + Ke \cos \omega$, the latter term being the perpendicular distance from the center of that chord on which the occupied focus of the ellipse is located. It will be remembered that A is the maximum positive and B the maximum negative velocity in the line of sight. By Schwarzschild's ingenious device we next obtain the time T of periastron passage and the $\frac{dz}{dt}$ component of the periastron above the S-axis. This gives us at once

[1] *Astronomische Nachrichten*, **136**, 17, 1894.

[2] *Ibid.*, **152**, 65, 1900.

in the hodographic circle the position of the diameter on which the focus of the ellipse is located, and we obtain this point itself as the intersection of this diameter and the chord previously constructed. Thus we find ω and e, since the distance from the center to focus

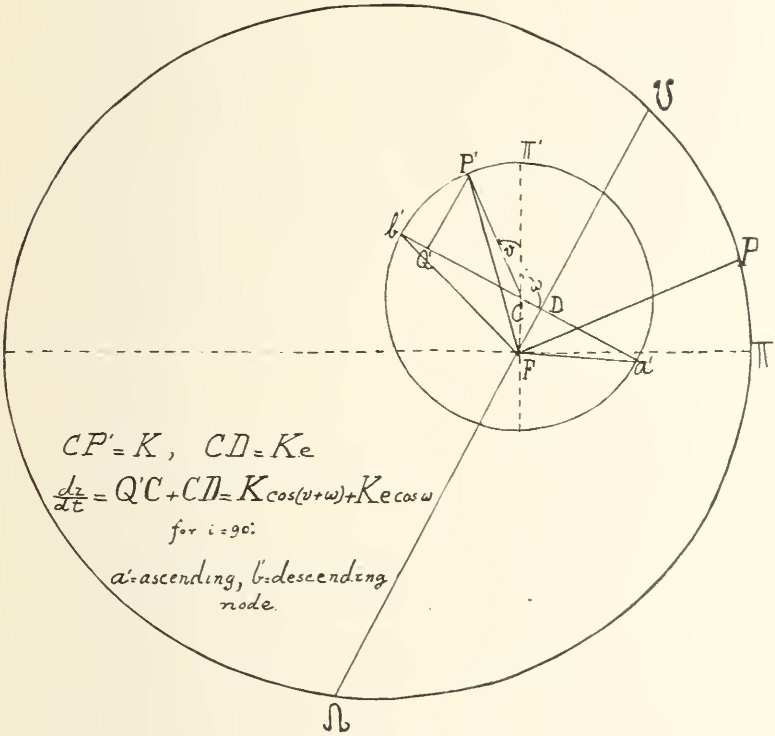


Diagram for case of χ *Draconis*

is $K \cdot e$. It seems that this procedure for finding ω and e will hardly ever lead into serious difficulties, so that the computer of orbits need not look for special precepts, as to the use of one or the other methods by which these quantities can otherwise be found.[1] It will prove to be very advantageous not to employ too small a unit for drawing the oscillating curve. The curve for χ *Draconis* by Wright[2] appears to be about

[1] See W. Zurhellen, *Astronomische Nachrichten*, **173**, 353; **175**, 245, 1907.

[2] *Astrophysical Journal*, **11**, 132, 1900.

what is desired; here the diameter of the hodographic circle comes out to be 2.5 inches.

Every point P on the ellipse (see figure) has its corresponding point P' on the hodograph, so that FP' (where F is the principal focus of the ellipse) gives the velocity of P both in magnitude and direction. The center C of the hodograph is at a distance $K \cdot e$ above F on the latus rectum, where K is the radius of the hodograph and e the eccentricity of the ellipse. The radius K is $= \frac{f^2}{c}$, where the constant of attraction f is either $\kappa \cdot \sqrt{m+m'}$ or $\frac{\kappa \cdot m'^{\frac{3}{2}}}{m+m'}$. The first value is used when we deal with the motion of a particle m with respect to a particle m', while the second value pertains to the motion of m with reference to the center of gravity of m and m'. The true anomaly v of the point P in the ellipse reappears in the hodograph at the center C, so that we write the expressions for the rectangular co-ordinates of P and P' as follows:

Point P

$$\xi = r \cdot \cos v \qquad (1)$$
$$\eta = r \cdot \sin v$$

Point P′

$$\xi' = K \cdot \cos (90^\circ + v) \qquad (1')$$
$$\eta' = K [e + \sin (90^\circ + v)].$$

The positive ξ-axis points toward the periastron point Π, and the positive η-axis to a point of true anomaly 90°. It is important to notice that if P_1 and P_2 are two points in the ellipse at the end of a focal diameter, then the corresponding points P_1' and P_2' will be at the extremities of a diameter of the hodograph.

The orbit of the binary intersects the tangential plane at F in the line of nodes. A system of three rectangular axes is so constructed that the positive z-axis coincides with the normal to the tangential plane away from the observer; the positive x-axis points to the ascending node of the particle m, and the positive y-axis to a point 90° ahead in the motion of the particle. To find the ascending node, we will say that it is that one of the two nodal points, where m attains positive z-components. Since we have put $i = 90$, we derive from our

figure at once the expression for the component of the velocity V which is perpendicular to the line of nodes. We obtain

$$\frac{dz}{dt}=K(e\cos\omega+\cos u) \tag{2}$$
$$\omega=a'C\,\Pi'$$
$$u=a'CP'$$

(a' and b' are the points in the hodograph which correspond to the ascending and descending node respectively).

Equation (2) is obtained by projecting the velocity $V=FP'$ on the line $b'a'$. It is evident that if we elevate our line of nodes by $Ke\cos\omega$, so that we refer the velocities to the diameter parallel to the line of nodes, we shall find that the observed velocities should with respect to $u=v+\omega$ fulfil the sine-curve if no perturbations prevail in the system. If we call this diameter the "nodal" diameter we can say that points which differ by 180° in their true anomaly will have equal and opposite radial velocities with respect to the nodal diameter. Schwarzschild's clever procedure to find the time T of periastron passage makes use of this very property. It seems not to be used as extensively as it should be; it is both a very reliable and quick mode of finding T. In the majority of cases the velocity γ of the center of gravity is already determined when the curve of oscillation is published, otherwise this must be done in the usual fashion.

Explaining now further the mode of proceeding by the hodographic curve, we assume that γ, T, and U (period) have been obtained. From the maximum and minimum velocities we find

$$K=\frac{A-B}{2} \text{ and } Ke\cos\omega=\frac{A+B}{2}.$$ (It is assumed that A and B are corrected for γ.)

We therefore construct a circle with radius K and measure off $Ke\cos\omega$ from the center C along a diameter; at the end of this distance we erect a perpendicular on the diameter. On this chord the focus F must be located. To obtain F we enter the curve of oscillation and measure the $\frac{dz}{dt}$ component of the periastron above Schwarzschild's axis of symmetry (which corresponds to the nodal diameter above). At the perpendicular distance equal to this ordinate we draw in the

hodograph a chord parallel to the nodal diameter. Of the two points of intersection but one will fulfil the condition to fall on the proper arc between ascending and descending node. The ambiguity whether the periastron point in the hodograph lies above or below the nodal diameter is easily settled. Let us call "periastron arc" that arc of the ellipse which terminates at both ends at the latus rectum and contains the periastron. Then we see that whenever $A > B$ the ascending node will be on the periastron arc; for $A = B$ the ascending node will be on the latus rectum of anomaly 90° if the time from the ascending node to the descending node is longer than that from the descending to the ascending node; if not, the ascending node is on the latus rectum where $v = 270°$. From the curve of oscillation we can therefore settle the ambiguity in the position of the periastron without difficulty. Whenever $A = B$ we have either a circular orbit or an elliptic orbit with $\omega = \left\{ \begin{matrix} 90° \\ 270° \end{matrix} \right.$. After the periastron point has been located on the hodograph we draw the diameter which passes through it. This diameter cuts the nodal chord in F, and measuring CF in terms of the radius K with a finely graduated scale (100 parts to an inch is a very suitable subdivision), we obtain e, and by measuring the sine-line of the periastron point we obtain ω.

Finally we make use of the equation of areas $r^2\, dv = c \cdot dt = K \cdot p \cdot dt$, and integrating over the entire ellipse, we get $\pi ab = K \cdot p \cdot U$, or $a = \frac{2K}{\mu}\sqrt{1 - e^2}$, where $\mu = \frac{2\pi}{U}$. We must not forget, that to make our formulas comparable to those generally used, we should replace K by $K \sin i$ whenever this quantity enters.

It will not be out of place to show by an example how very rapidly this geometric proceeding leads to an evaluation of the elements. After Vogel's thorough investigation of the orbit of *β Aurigae*[1] it seems superfluous to adhere to the set of observations by which Rambaut, Lehmann-Filhés, and Schwarzschild have tested their methods. I have selected therefore instead the stars *χ Draconis* and *η Aquilae*, which have been so ably discussed by Wright.

I. *χ Draconis*.[2]—The curve of oscillation on page 132 seems to be drawn with extreme accuracy. In order to avoid errors by using

[1] *Astrophysical Journal*, 19, 360, 1904. [2] *Ibid.*, 11, 131, 1900.

a self-made subdivision of the scale contained in the diagram, all measurements were made with a metallic scale of 100 graduations to an inch.

By actual measurement we find

$$A=+321 \quad \text{(not yet corrected for } \gamma)$$
$$B=+\ 72$$
$$K=\frac{A-B}{2}=124.5$$
$$\gamma+Ke\cos\omega=\frac{A+B}{2}=196.5.$$

Wright gives $\gamma=32.2$ km; this on the scale employed is equal to 220. Hence $Ke\cos\omega=-23.5$; the negative sign indicates that Schwarzschild's axis is 23.5 below the γ-axis given by Wright. By Schwarzschild's method of reflection and translation by $U/2$ along the time-axis we obtain the following four points of intersection of the original curve and its superimposed image:

1899	March	9.2
	April	15.6
	July	26.9
	Sept.	4.2 .

From the condition that the interval of time between a pair of dates must be $140^d5=\frac{U}{2}$, and at the same time that the corresponding velocities above Schwarzschild's axis should be equal and of opposite sign, we single out March 9.2 and July 26.9 as the only possible pair of dates. Of these July 26.9 is the periastron point, because the curve of oscillation is here decidedly steeper than at March 9.2. Since the periastron point is below the axis, its corresponding point on the hodograph must be below the nodal diameter. We next draw the hodographic circle with $K=124.5$. Since $A<B$ (measured from the γ-axis), we see that the ascending node must be on the apastron arc of the ellipse, while the descending node is on the periastron branch. In the hodograph, periastron and focus lie on opposite sides of the center of the hodograph; since Π' is near to b' we must draw in the hodographic circle the chord at a central distance of $Ke\cos\omega=23.5$ *above* the center. Next we measure off $56.5=\frac{dz}{dt}$

of the periastron and find the point Π' on the hodograph. The diameter through Π' meets the nodal chord in F. We measure off by the scale $CF=53$; therefore $e=\frac{53}{124.5}=0.426$. Similarly $\sin(\omega-90)=\frac{60}{124.5}\;\therefore\;\omega=118^\circ\,49'$. When we compare the values of the elements derived by our method with those obtained by Wright after the procedure of Lehmann-Filhés, we have:

	Wright	Laves
T	1899, July 27.0	1899, July 26.9
e	0.45	0.426
ω	$114.^\circ 99$	$118^\circ\ 49'$.

Wright has derived a second set of elements by a method of least-squares solution, and his final values are

$$T=1899,\ \text{July}\ 28.^{d}3\pm 0.^{d}5,$$
$$e=0.423\pm 0.006,$$
$$\omega=119^\circ\ 0'\pm 1.^\circ 1.$$

It is rather remarkable that our first set of elements comes so very close to these improved values. The remaining elements, U and $a \sin i$, are in no way altered by my procedure and are therefore not quoted. It should be remarked that the time consumed in the determination of an orbit by this geometric method is very short indeed, and it is therefore well suited for a check-determination of orbits obtained by other methods. Moreover, the least-squares solution, which one is bound to use with well-determined stars, gains not a little by this graphical method.

II. *η Aquilae.*[1]—Figure 1 in Wright's paper, gives the curve of oscillation; from it we obtain by an analogous procedure with the one under (I):

$$A=+\ 37\,,\qquad \frac{A-B}{2}=K=77\,,$$
$$B=-117\,,\qquad \frac{A+B}{2}=Ke\cos\omega+\gamma=-40\,,$$

From the figure $\gamma=-53.5\,.$

Hence $Ke\cos\omega=+13.5\,.$

[1] *Astrophysical Journal*, 9, 60, 1899.

This axis we draw $+13.5$ parts above the γ axis. By Schwarzschild's method we obtain $T=6^{\mathrm{d}}.24$ and the corresponding $\frac{dz}{dt}$ is 29. The periastron point is above the axis *S;* when we subtract γ from *A* and *B* we see that $A>B$, the ascending node is on the periastron branch. From the hodograph and the quantities mentioned we obtain

$$\begin{array}{c}\text{Laves}\\ \left.\begin{array}{l} e=0.44 \\ \omega=67^\circ\ 53' \\ T=6^{\mathrm{d}}.24 \end{array}\right\}\end{array} \text{ as against } \begin{array}{c}\text{Wright}\\ \left\{\begin{array}{l} e=0.47 \\ \omega=65^\circ.79 \\ T=6^{\mathrm{d}}.176 \end{array}\right.\end{array}$$

Wright's second determination by the method of least squares gives

$$\begin{array}{l} e=0.489\pm 0.014 \\ \omega=68^\circ\ 55'\pm 1^\circ.95 \\ T=6^{\mathrm{d}}.210\pm 0.028^{\mathrm{d}}. \end{array}$$

THE UNIVERSITY OF CHICAGO
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DETERMINATION OF WAVE-LENGTHS OF LIGHT FOR THE ESTABLISHMENT OF A STANDARD SYSTEM[1]

By PAUL EVERSHEIM

The knowledge of the wave-length of light to a few thousandths of an Ångström unit is important for many spectroscopic and astronomical purposes. This accuracy is attainable with a large grating by interpolation between neighboring standards, but the standards themselves cannot be obtained with a grating, as the method of coincidences fails. Hence it is necessary in establishing a system of standards to use some one of the interference methods, of which that of Perot and Fabry seems to me to be the most practical. The decision of the International Solar Union (Oxford meeting) was followed that the standards should at most not be farther separated than 50 Å, and that numerical values should be determined as far as possible with an accuracy of 1/1000 of an Ångström unit.

The method may be described as follows. For producing the phenomena, use is made of a so-called "silvered air-stratum." This is obtained by setting up two plane-parallel glass plates, figured as accurately as possible, with a thin silver coat on one side, and then adjusted to accurate parallelism with the silvered surfaces toward each other. If a cone of converging homogeneous light then passes through the air-stratum so formed, the observer employing a telescope focused on infinity will see from the back side a number of concentric rings, a phenomenon of interference which is produced in the same manner as that of thin plates—as can be clearly seen from Fig. 1.

Let $S' \ldots . S$ be parallel rays of a beam of homogeneous light of wave-length λ, meeting the air-stratum at an angle of ϕ. The rays in part pass directly through the stratum, but another portion is reflected within it. If an incident ray then interferes with a reflected ray, it generally will have a difference of path with reference to the former, which we will call δ, and if δ/λ is a whole number, the two rays will reinforce each other. But since the incident rays are reflected very frequently, not only will the neighboring ray contribute its portion δ, but also the

[1] Translated from *Zeitschrift für wissenschaftliche Photographie,* 5, 152–180, 1907.

following will give 2δ, the third 3δ, etc., whence we see that an increase of the intensity is produced according to the degree of the reflection. This occurs only for the case mentioned when δ/λ is an integer, i. e., for a definite angle of incidence. The rays, however, are incident under all possible directions, and in the general case δ/λ differs from a whole number. But the slightest deviation will also ultimately lead to a difference of path on account of the great number of reflections, which is for an incident ray the value of $\lambda/2$, in which case extinction will result. It follows from this that only the rays which are so incident upon the air-stratum that they receive a difference of path of λ, 2λ, ... $n\lambda$, can be reinforced by interference, while all the rest must be rendered more or less faint; in this process the larger number of rays will participate according to the frequency of the reflection and the degree of silvering; whence we reach the further conclusion that the interference phenomena will increase in distinctness in the same measure.

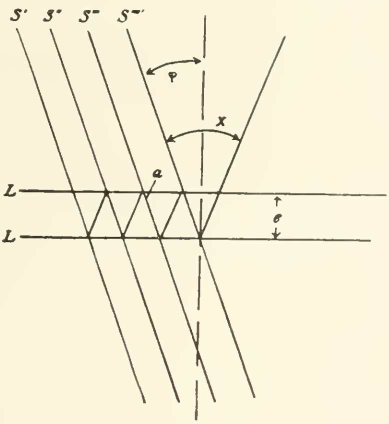

Fig. 1

A number of rings separated from each other by broad dark intervals may now be seen in a telescope focused on infinity, since the incident rays are symmetrically distributed about the axis of observation. On bringing the paths closer together, one after another of these rings moves in toward the center and there vanishes until the whole phenomenon has disappeared at the distance zero; and conversely, one ring after another becomes visible as the paths are separated. The first ring appears when the difference of path of two interference rays has become equal to a wave-length of the particular kind of light, the second at a difference of path of two wave-lengths, etc., and we may accordingly speak of a first and second order of the rings, and so on, which we will designate with the letter P.

If two beams composed of homogeneous light are incident simultaneously, but of which the one has only rays, say, of the red line of cadmium, while the other has only rays of the green cadmium line, then we should observe two systems of rings; then if the distance of the path is sufficient, it is not difficult to recognize that a red ring is superposed upon a green ring, at definite intervals so that they coincide. If an exact coincidence is observed, that is, one in which a red ring precisely covers a green one, and if we know the order P and P' of the rings at this place, then we shall have the relation

$$P\lambda = P'\lambda',$$

where λ and λ' denote corresponding wave-lengths. If λ is known, the unknown wave-length may be computed by the formula

$$\lambda' = \frac{P\lambda}{P'}.$$

For determining the number of the order Perot and Fabry constructed a so-called interferometer, an apparatus permitting the two silvered plates to be displaced parallel to each other. In principle their measurement consisted simply in departing from zero to determine the number of the order by counting, an exceedingly wearisome task, but one, however, which Perot and Fabry nevertheless carried out for some of the mercury lines.

By modifying the interferometer Perot and Fabry then constructed an apparatus which was far more convenient in operation and which above all was unaffected by the unavoidable disturbing vibrations. It was with such an apparatus at a definite separation of the two silver strata that the author made his observations, and it is probably necessary to describe the apparatus pretty fully.

So far as the theory of the phenomena is concerned, the matter is very simple and leads very quickly to the method which must be used for definitive computation. Let us refer again to Fig. 1 and assume that we are observing the rings of the green cadmium line in the manner described above.

The separation of the plates, hence the thickness of the air-stratum, may be called e, corresponding to a wave-length λ, when we shall obviously have

$$2e = P\lambda; \text{ hence } \lambda = \frac{2e}{P},$$

this applying to the case of vertical incidence of the rays, hence here for the center. But if the incident rays make the angle ϕ with the normal, we shall have

$$P=\frac{1}{\lambda}\left(\frac{2e}{\cos\phi}-a\right),$$

or, since $a=2e\tan\phi\sin\phi$,

$$P=\frac{1}{\lambda}\left(\frac{2e}{\cos\phi}-\frac{2e\sin^2\phi}{\cos\phi}\right),$$

which becomes

$$P=\frac{2e}{\lambda}\cos\phi .$$

We can develop the cosine function in a series, and neglect the higher powers, as ϕ is very small. We then arrive at the expression

$$P=\frac{2e}{\lambda}\left(1-\frac{\phi^2}{2}\right). \tag{1}$$

If a beam of a different wave-length λ' is incident, we get similarly

$$P'=\frac{2e}{\lambda'}\left(1-\frac{\phi'^2}{2}\right). \tag{2}$$

The last two equations give us the means for computing the unknown wave-length λ', after we have made one experiment each for the same separation of the plates with comparison light of the wave-lengths λ and λ', and have measured the angles and have in any way whatever obtained the number of the orders P and P'. If in place of the angle of incidence ϕ, we substitute the angle actually to be measured, $x=2\phi$, or $x'=2\phi'$, then the expression in brackets will take the form

$$1-\frac{x^2}{8} \quad \text{and} \quad 1-\frac{x'^2}{8} .$$

Taking account of this in equations (1) and (2), and considering that the high powers of x may be neglected on account of the smallness of the angle, we get the simple equation

$$\frac{P'}{P}=\frac{\lambda}{\lambda'}\left(1+\frac{x^2}{8}-\frac{x'^2}{8}\right), \tag{3}$$

or

$$\lambda'=\lambda\frac{P}{P'}\left(1+\frac{x^2}{8}-\frac{x'^2}{8}\right). \tag{4}$$

As source of the comparison light, the wave-length of which must be very accurate, we are fortunately in possession of data of an extremely high degree of precision, thanks to the excellent measures of Michelson.[1] These are the lines of the cadmium spectrum,[2] of which the red line is better adapted for comparison, while the green one is commonly more convenient for use. The details will be discussed later.

The determination of the numbers of the order appears at first somewhat difficult. It is, however, easy to compute P' in case P has been previously determined, and a series of measures has been made for the appropriate wave-lengths. The wave-length λ' which is to be measured is in general accurately enough known so that P' can at least be approximately computed from equation (3); that is, it may be established that the error amounts to only a few units of the second decimal of a whole number, the number of the order, which can be only a whole number; the actual value must then be the nearest whole number to this value. The determination of P is, however, not so simple. For this Perot and Fabry used their interferometer, but the mode of measurement, which I shall not discuss in detail here, offers the same difficulties which arise in determining the wave-length by the method of coincidences described above and in counting the rings; and it seems to me that the method suggested by Lord Rayleigh[3] for P is very much more simple. This method is as follows.

If the silvered air-stratum of a definite thickness has been arranged as a standard with which the measurements are to be undertaken, a series of experiments is first made with various kinds of light of known wave-length. The distance of the silver stratum can now be measured to an accuracy of $\frac{1}{100}$ of a millimeter, whence is obtained an approximate value for the number of the order from $P=\frac{2e}{\lambda}$. For instance, if $e=3.19$ and $\lambda=5085$, we obtain the number 12550; from this we know that the value for P, if not precisely this number,

[1] "Détermination expérimentale de la valeur du métre en longueurs d'ondes lumineuses," *Travaux et Mémoires du Bureau international des poids et mesures*, 11.

[2] Fabry has expressed his readiness to test Michelson's value by another method; and the work is now nearly completed.

[3] "Some Measurements of Wave-length with a Modified Apparatus," *Phil. Mag.*, 11, 685, 1906.

certainly must lie in its neighborhood; and if e has been measured pretty closely, it may be assumed with safety that P is to be found above 12550.

We therefore proceed from this number and compute by equation (3) P' for a wave-length λ', after we have determined x or x' by experiment. If no whole number is found for P', the same computation will be made at 12551, etc., until we come to a value where P' is a whole number. This, however, might be an accident, and in order to be entirely certain, we take perhaps five wave-lengths, computing for each the corresponding number of the order after the experiments have been made always with the same source of light. The values are then collected in a table, and ultimately must form a series consisting solely of whole numbers. Of course the measurement here need not be so exact as is necessary in the determination of wave-lengths; and we may content ourselves with a single photograph and measurement, even if slight deviations now arise from this cause, which, however, are not of importance. I give below a series from the table for determining P.

$e = 3.19$ mm

Cd			*Hg*			
Red	Green	Blue	Yellow 1	Yellow 2	Green	Violet
9897.02	12529	13275.02	11004.04	11044.0	11669.04	14620.0

For the comparison line *Cd* 5085.224 we therefore get, without any uncertainty, $P = 12529$ for a separation of the plates $e = 3.19$. The computation of the number of the order, and of course also of the wave-length, presumes the knowledge of the angle x or x' at which a ring is formed, for the comparison light as well as for the light under investigation. These values can be obtained directly in degrees, minutes, and seconds if the pair of plates is mounted on the table of a goniometer, and if the measurements are made with telescope and cross-hairs in the ordinary way. This method furnishes usable results if the observer has a good instrument, and the lines concerned are very bright. But in most cases the observations deal with a very faint light so that direct measurement is exceedingly wearisome and unreliable. The photographic method is therefore to be preferred, and indeed its use is practically required.

The measurement proper is thus somewhat altered, as we shall now explain.

Each element of the ring is formed by parallel rays which are united by the lens L in their focal plane, that of the photographic film. The angle for a ring evidently has its vertex in the principal point of the lens. Therefore if we know the focal length R of the lens, and measure the diameter of the ring D, we shall get, remembering that x is very small,

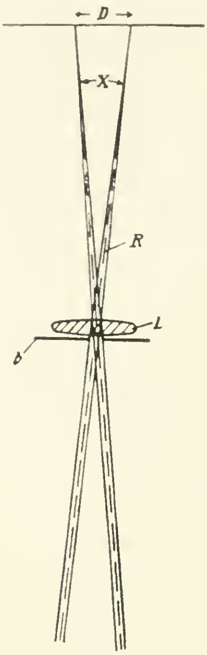

FIG. 2

$$\tan x = x = \frac{D}{R}.$$

Thus for the final computation, equation (4) takes the form

$$\lambda' = \frac{P\lambda}{P'}\left(1 + \frac{D^2}{8R^2} - \frac{D'^2}{8R^2}\right). \qquad (5)$$

ARRANGEMENT OF EXPERIMENT AND MODE OF MEASUREMENT

As already mentioned, for the computation of wave-length by the interference method, a source of light is necessary for a comparison which contains a line that can be accurately determined and has been accurately measured. As we have already seen, such lines occur in the cadmium spectrum, and for comparison the green line which was determined by Michelson was selected. In his experiments Michelson used the tube which bears his name, a somewhat modified Geissler tube, which was provided with a few crystals of cadmium metal, and which when excited in the usual way yielded the spectrum of cadmium. The lines are, however, rather faint and are not well adapted for work with the interference apparatus. A most disagreeable fact is that such tubes very soon become inactive and after only a few experiments they may crack at any place whatever. It was very fortunate for me, then, that a cadmium arc lamp from the quartz works of the firm Heraeus in Hanau was recommended to me which left nothing to be desired in the way of brightness and purity of the spectrum. This

lamp consists of a ∩-shaped quartz tube, the two arms of which are filled with cadmium in the lower wider portion, which is in metallic contact with the nickel-steel electrode fused into the quartz wall. The arms are cooled with water and the arc passes over the upper closed part. The lamp is kindled by an induction spark after previous warming, and it requires a current strength of four amperes. The arc is best maintained at a tension of 220 volts. It is necessary to leave the air-pump attached, as it is often required during its use to again pump out air. If the lamp is well mounted, these disturbances need not be feared, and it will render very excellent service. I have already burned this one several hours without having to change

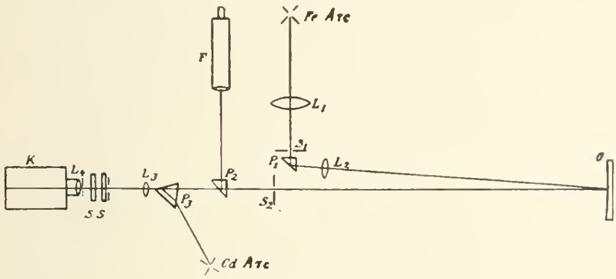

FIG. 3

anything about it. The objection can be raised, it is true, that the lines used of the spectrum produced under these altered conditions are not identical with those of Michelson's tube. A more accurate test which I applied to the red and green lines, however, indicated that a difference in the wave-length could not be established, so that the lines of the arc lamp could be used for comparison without fear.[1]

All of the observations were made by means of photographic plates. This procedure has the advantage over the direct observation of preserving by a longer exposure phenomena which are in part very faint; then one can always check up his earlier measurements on the plates, and above all can undertake investigations of the spectrum in the invisible portion. The arrangement of the apparatus can be seen from Fig. 3.

[1] See Michelson, *loc. cit.* He tested the *Cd* lines under the most varied conditions, such as alternation of pressure, temperature of tube, and strength of current. He made experiments with old tubes, compared these with new ones, took commercial cadmium, used chemically pure cadmium; he always obtained the same values for the wave-lengths.

The iron arc burning with 5 to 6 amperes casts its light by means of the lens L_1 on the slit S_1. The beam is then passed by the totally reflecting prism P_1 through the lens L_2 on a medium-sized Rowland concave grating G, so that a sharp iron spectrum is obtained in the plane of the slit S_2. For purposes of orientation in this spectrum the telescope S is employed, which is set on the slit S_2, after the prism P_2 has been brought to the proper place, and then is brought into coincidence with the cross-hairs. S_2 is now removed and a rotation of the grating makes the line under investigation come into coincidence with the cross-hairs as the slit did previously. If we then bring the slit S_2 back to its former position and remove P_2, we can project by the lens L_3 an image of the illuminated slit through the silvered air-stratum between the plates *ss* on the small diaphragm of camera *k*. The incident rays of the wave-length in question interfere and we obtain from the cone-shaped beam in the focal plane of the quartz lens L_4 (f=circa 15 cm) a system of rings which can be photographed. The comparison line is obtained by means of the prism of carbon bisulphide P_3 from the cadmium arc as source, and it is brought to the correct position by turning the prism.

For the iron arc I employed a lamp with hand regulation, and at 220 volts tension made the arc as long as possible. When this was the case and the lamp was burning quietly, I obtained very good plates. It is true that such an arc sorely tries the patience of the observer, burning often for a good quarter of an hour without disturbance, whereupon it suddenly makes the wildest leaps and is only with difficulty quieted down. I have also used the iron arc in a vacuum, but the flickering was even worse here.

The movable portion of the whole apparatus was adapted to the requirements so that with suitable tracks and slides the alterations desired could be undertaken in the dark and the slit and prisms brought to the proper place.

THE CONDITIONS FOR PROPER OPERATION

I. THE PARALLELISM OF THE AIR-STRATUM

As we have already frequently seen, our experiments require a silvered air-stratum of definite thickness. For this we use two glass

plates, and in order to set these up at a definite distance, we need separators. These are applied at three points at the edge of the plates, which are then pressed together by rings, as may be seen from Fig. 4, in which *a* shows the plan, and *b*, the section, exhibits the mechanism. The stiff iron casting *E* has an aperture in the center, at the edge of which a flange *w* is turned. After one plate is placed in this flange, the small balls *d* which separate the plates are put in place and covered with the other plate. A spring *f*, adjustable lengthwise and also capable of being clamped, is attached to each of the three

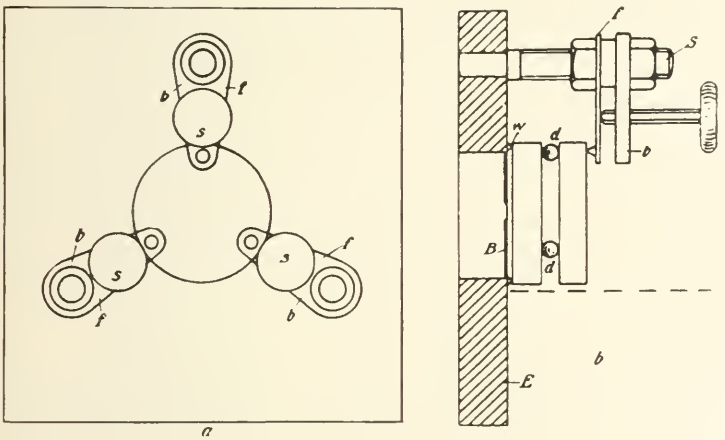

Fig. 4

bolts *S*. The piece *b* carries the screw *s* by which the pressure on the spring can be adjusted independently of the position with respect to the bolts.

The balls were as hard as glass and figured with an astonishing accuracy. As soon as the apparatus is put together, the interference rings are seen in homogeneous light, which can be accurately adjusted by a slight pressure of the ring *f* by the screw *s* in bringing the two plates into accurate parallelism. This adjustment is in fact the principal problem of the experimenter. We saw above that the computation of the wave-length required a knowledge of the angle x at which the ring is formed. The slightest change in the separation of the plates also alters the diameter of the ring and with it the angle x.

Therefore if the air-stratum is wedge-shaped, however slightly, this will change, if the incident rays are displaced in the direction of the wedge. When work is done with different sources of light it is readily possible that the effective rays do not always strike the pair of plates at the same place, whence errors must result from a wedge-shaped air-stratum.

This peculiarity, that the diameter of a ring changes with the slightest change in the distance of the plates, offers at once the means of adjustment, for which purpose the plate-holder of Fig. 4 is mounted on a stand which permits it to be displaced in both a horizontal and a vertical direction. Thus we can make the rays pass through very different parts of the plates, and can vary the pressure of the spring *f* until no variation in the size of the ring is longer perceptible in a region of about 3 cm diameter. But in order to render harmless anything still erroneous in the adjustment and any casual unevenness of the silver stratum, a diaphragm with an aperture of 3 mm is in the different experiments placed across in front of the plate; similarly a diaphragm of 1.5 mm aperture is placed in the camera lens.

2. THE UNIFORMITY OF THE SILVER FILM

The silvering of the plates must be effected with the greatest of care and any irregularities of thickness, and cloudiness must be avoided or at least reduced to a minimum, as otherwise the same errors would arise as are shown under 1. The silvering must be also carried to a certain definite degree; if it is too heavy, then too little light will penetrate and the phenomena will be indistinct; while if it is too weak, we shall have too few reflections and the rings will be lacking in sharpness. A correct density of silvering is determined by experiment.

3. ALLOWANCE FOR THE ERRORS OF THE LENS

The diaphragm *b* provides that all of the rays pass through the center of the lens *L* (Fig. 2). The distance of the lens from the photographic film is constant for all the plates, so that we have a mean focal length *R* remaining always the same. Mathematically considered, light of only a definite wave-length can then be sharply focused, but

in practice the differences are so small as to be inappreciable, and we may also simplify in this respect without fear of the consequences. A test of the result shows that a good scale is sufficient for the determination of R and it will be enough if the tenth of a millimeter is accurate. Moreover, it would be useless to attempt a greater accuracy, since the distance of the photographic film may well vary during experiments through a tenth of a millimeter.

4. CORRECTION FOR CHANGE OF TEMPERATURE

Temperature changes can produce a very disturbing effect during the measurements; and the change of a tenth of a degree will, on account of the expansion of the steel balls, produce a very perceptible alteration in the diameter of the ring. Inasmuch as it is difficult to avoid temperature variations within this range, we must at least take care that the experiment is made when the temperature is either rising or falling with the greatest possible uniformity. An exposure to the source of the comparison light will then be made before and after the exposure of the line to be measured, and in the computation use will be made of the mean value from the two exposures.

5. TEST OF THE CHANGE OF PHASE

Equation (5), for the computation of the wave-length λ', assumes that the separation of the plates or the thickness of the silvered air-stratum is the same for λ' as for λ. This is, however, not the case, for the distance varies from wave-length to wave-length, for the well-known reason that according to the color a ray of light will penetrate to a greater or less depth in reflection from the silver films. Although this is excessively small even for the rays that penetrate the farthest, nevertheless the fact demands attention for precise measures; indeed, the thorough control in this respect is one of the principal problems in the measurement.

Experiment shows that the penetration into the silver film becomes greater with decreasing wave-length. We can assume that for the source of comparison light, in the case before us for the green cadmium line, the reflections take place for a distance compared with which the shorter waves all have a larger distance, the longer waves, on the

contrary, a smaller distance, just as if we were actually to change the distance correspondingly.

If we now determine the number of the order P of a ring[1] of light we must obtain a whole number; but if we undertake the same measurement for the red cadmium line, we shall observe the ring at a *smaller* distance; and since the number of the order also increases with the increasing distance, there must be added to the number of the order of the red line a small fraction ϵ, in order to make it refer to the greater distance, as is necessary. Conversely we shall have to subtract a corresponding amount for the shorter waves.

The absolute amount ϵ of this fraction cannot change if the separation of the plates is varied, inasmuch as the depth of the penetration

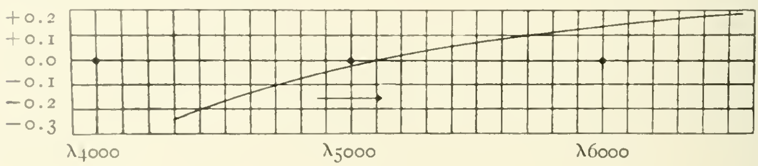

FIG. 5

into the film does not depend upon it. Therefore, if we make an exposure at a distance of the plates of 5 mm for the red cadmium line, and compute the number of the order, we shall obtain the value $P' + \epsilon$. If we repeat the experiment for a distance of 3 mm, we must get the value $P_0' + \epsilon$, where it is assumed that we accurately know the wave-length of the red cadmium line. If this is not the case, we may form two corresponding equations for the two different separations of the plates and thence compute the unknown quantities λ' and ϵ.

This peculiarity of the silver film now under discussion therefore requires for the definitive computation of the wave-lengths a table of corrections, or better a curve on which the change of P with the wave-length is graphically represented. In Fig. 5 the wave-lengths are drawn as abscissae, and the corresponding fraction ϵ of the number of the order as ordinates; here the change of phase ϵ for the green comparison line is placed equal to zero.

[1] In order that equations (4) and (5) shall remain correct, we may use in the measurement only the smaller rings situated at the center.

COMPUTATION OF THE RESULTS OF THE EXPERIMENT

Preliminary Remarks.—In what follows R denotes the mean focal length of the camera lens, D the diameter of the ring of the comparison light of the green cadmium line λ 5085.824, D' that of the wave-length to be measured. For determining the diameter I employed the excellent dividing engine of our laboratory, which has been used for measurements of grating spectra, and which is provided with a recording attachment from designs of Kayser;[1] R and D are expressed in units of the revolution of the screw $=\frac{1}{3}$ mm. The errors of this screw, which was made according to Rowland's method, are exceedingly small and do not come into consideration in the small range covered by the measures before us. In order to furnish the reader with an idea of the magnitude of the errors in the measurements of D and D', I give the following series of observations:

Cd, λ = 5085.82	*Cd*, λ = 6438.47	*Fe*, λ = 4494.57
D = 10.500	10.490	12.435
500	495	440
515	500	425
495	482	435
480	480	442
488	495	425
Mean = 10.496	10.490	12.433

The probable errors accordingly are:

For λ	
5085.82	±3.2
6438.47	±3.2
4494.57	±2.0

expressed in units of the last place.

If the thousandth of an Ångström unit is to be accurate, the errors must not be much larger than this.

All the values obtained, referred to the green cadmium line λ 5085.824, are collected in the following tables. Each line was measured twice on different plates at different times and at different temperatures. On each photograph the three innermost rings were employed so that for each wave-length six measures are available.

[1] *Handbuch der Spektroskopie*, 1, § 567.

COMPUTATION OF THE DISPLACEMENT OF PHASE ϵ FOR THE RED *Cd* LINE λ6438.4722

(A) SEPARATION OF THE SILVERED PLATES $e=4.75$ mm; $R=423.75$

	1	2	3	New Plate 4	5	6
Mean[1] from and	6.780 .730	11.090 .080	14.142 .138	9.576 .560	13.012 .000	15.726 .712
D	6.755	11.085	14.140	9.568	13.006	15.720
D'	10.650	14.500	17.560	7.877	12.613	16.082
$\frac{D^2}{8R^2}$	0.0000318	855	1392	637	1178	1720
$\frac{D'^2}{8R^2}$	0.0000718	1464	2146	432	1107	1800
Diff. + 1	0.9999529	0.9999391	0.9999246	1.0000205	1.0000071	0.9999920
P	18684	18683	18682	18684	18683	18682
P' by (5)	14758.014	14757.002	14757.02	14759.013	14758.02	14757.014
∴ ϵ	+0.014	+0.02	+0.02	+0.013	+0.02	+0.014

The mean of these six values of the change in phase is $\epsilon=0.017$

[1] Mean value on account of change of temperature.

(B) SEPARATION OF THE SILVERED PLATES $e=3.19$ mm; $R=426.75$

	1	2	3	New Plate 4	5	6
Mean of and	10.485 .465	15.057 .023	18.532 .500	10.510 .496	15.080 .052	18.550 .545
D	10.475	15.040	18.516	10.507	15.066	18.552
D'	11.490	16.725	20.690	10.490	16.040	20.120
$\frac{D^2}{8R^2}$	0.0000753	1553	2353	757	1558	2362
$\frac{D'^2}{8R^2}$	0.0000906	1920	2938	755	1766	2778
Diff. + 1	0.9999847	0.9999633	0.9999415	0.0000002	0.9999792	0.9999584
P	12532	12531	12530	12528	12527	12526
P'	9899+0.022	9898.018	9897.015	9896.015	9895.017	9894.02
ϵ	+0.022	+0.018	+0.015	+0.015	+0.017	+0.02

The mean value of the change of phase $\epsilon=0.018$

From the two mean values $\epsilon=0.017$ and 0.018 for the different distances we may therefore construct the upper branch of the curve in Fig. 5. The lower part of the curve, as explained below, is drawn from the values of Perot and Fabry.

I now give the values from a number of iron lines which I selected at certain distances in the iron spectrum, choosing such lines as were recently determined by C. Fabry and H. Buisson.[1] The values of P' were always corrected by the curve of Fig. 5.

(*C*) SEPARATION OF THE PLATES $e=4.75$

Fe λ 4282.411 (Fabry and Buisson). $R=423.75$

				New Plate		
	7.522 .505	11.593 .580	14.564 .542	6.110 .100	10.704 .700	13.860 .830
D..........	7.513	11.586	14.553	6.105	10.702	13.845
D'..........	8.644	11.832	14.340	13.613	10.956	15.805
$\frac{D^2}{8R^2}$..........	0.0000393	934	1474	260	797	1334
$\frac{D'^2}{8R^2}$..........	0.0000520	974	1431	1290	835	1739
Diff.+1.....	0.9999873	0.9999960	1.0000043	0.9998970	0.9999962	0.9999595
P..........	18684	18683	18682	18684	18683	18682
P'..........	22188.975	87.975	86.975	86.975	87.975	85.975
λ'..........	4282.4127	.4127	.4117	.4117	.4127	.4136

Mean, 4282.4125

This differs from Fabry and Buisson by +0.001 Å.

Fe λ 4375.939 (Fabry and Buisson). $R=423.75$

	10.308 .252	13.558 .508	16.157 .100	6.070 .055	10.705 .676	13.825 .830
D..........	10.280	13.533	16.128	6.062	10.690	13.828
D'..........	9.753	12.709	15.080	10.150	13.052	15.370
$\frac{D^2}{8R^2}$..........	0.0000735	1275	1811	256	795	1331
$\frac{D'^2}{8R^2}$..........	0.0000662	1124	1583	717	1186	1644
Diff.+1.....	1.0000073	1.0000151	1.0000228	0.9999539	0.9999609	0.9999687
P..........	18683	18682	18681	18684	18683	18682
P'..........	21713.98	12.98	11.98	13.98	12.98	11.98
λ'..........	4375.9424	.9444	.9454	.9444	.9414	.9434

Mean, 4375.9435

This differs from Fabry and Buisson by +0.004 Å.

[1] *Comptes Rendus*, **143**, July 1906.

Fe λ 4494.576 (Fabry and Buisson). $R=423.75$

	9.241 .227	12.740 .730	15.505 .468	10.355 .312	13.605 .570	16.183 .152
D	9.234	12.735	15.486	10.333	13.587	16.168
D'	8.018	11.489	14.161	9.268	12.407	14.920
$\frac{D^2}{8R^2}$	0.0000593	1129	1669	743	1285	1820
$\frac{D'^2}{8R^2}$	0.0000447	919	1396	598	1071	1550
Diff. + 1	1.0000146	1.0000210	1.0000273	1.0000145	1.0000214	1.0000270
P	18683	18682	18681	18683	18682	18681
P'	21140.98	39.98	38.98	40.98	39.98	38.98
λ′	4494.5802	.5812	.5812	.5812	.5833	.5802

Mean, λ=4494.5812

This differs from Fabry and Buisson by +0.005Å.

Fe λ 4859.759 (Fabry and Buisson). $R=423.75$

	8.730 .757	12.447 .428	15.221 .245	7.560 .542	11.6 .0	14.627 .615
D	8.744	12.437	15.233	7.551	11.626	14.621
D'	9.322	12.702	15.328	8.168	11.898	14.737
$\frac{D^2}{8R^2}$	0.0000532	1076	1615	396	941	1488
$\frac{D'^2}{8R^2}$	0.0000605	1123	1635	464	985	1512
Diff. + 1	0.9999927	0.9999954	0.9999980	0.9999932	0.9999956	0.9999976
P	18684	18683	18682	18684	18683	18682
P'	19552.99	51.99	50.99	52.99	51.99	50.99
λ′	4859.7606	.7606	.7617	.7629	.7617	.7606

Mean, λ=4859.7613

This differs from Fabry and Buisson by +0.002Å.

The accompanying data have been given in the first instance to illustrate the adequacy of the method. Some of the measurements are entirely satisfactory in regard to their agreement, while for others deviations as large as 0.006 units occur. This is obviously due to the intensity or structure of the line under investigation, the diameter of whose ring is determined with less exactness. To get an idea of how easily

Fe λ 5232.960 (Fabry and Buisson). $R = 423.75$

	7.487 .481	11.600 .624	14.598 .582	5.973 .934	10.637 .631	13.782 .776
D..........	7.483	11.612	14.590	5.954	10.634	13.779
D'.........	10.410	13.726	16.405	9.300	12.873	15.674
$\frac{D^2}{8R^2}$.........	0.0000390	938	1482	247	787	1321
$\frac{D'^2}{8R^2}$.........	0.0000754	1311	1873	602	1153	1710
Diff. + 1.....	0.9999842	0.9999627	0.9999609	0.9999645	0.9999634	0.9999611
P..........	18684	18683	18682	18684	18683	18682
P'..........	18158.0	57.0	56	58	57	56
λ'..........	5232.9602	.9626	.9614	.9650	.9662	.9626

Mean = 5232.9630

This differs from Fabry and Buisson by +0.003Å.

errors can occur, it should be considered that a deviation of a thousandth of an Ångström unit corresponds to an error of 0.005 (=0.0016 mm) in the measurement of the diameter of the ring, D being taken as equal to 13 in the average, and D' assumed to be correct. The conditions are indeed somewhat more favorable to the computation for the smaller rings, but the error of reading on account of the lack of sharpness of the rings doubtless increases in a similar degree, so that nothing is gained thereby. When we recall that the results were obtained under the most varied conditions, that large and small rings were taken, that comparisons were made with rings of higher and of lower order, that different photographs were used, etc., we obtain a certain confidence as to the correctness of the figures. It is nevertheless surprising that the values found here are all larger than those of Fabry and Buisson; this leads to the suspicion that the deviations come from some systematic cause, and it will be the next duty to seek this where the weak side in the method lies. There is no doubt but it will be found to lie in the displacement of phase. Thus Lord Rayleigh[1] finds a decidedly larger difference between the green and red cadmium lines than I have and than was established by Perot and Fabry.[2]

[1] *Loc. cit.*, p. 700.

[2] *Astrophysical Journal*, 15, 95, 1902.

The results are:

Perot and Fabry	$\epsilon = 0.013$
Eversheim	$= 0.018$
Lord Rayleigh	$= 0.050$

It is striking that Rayleigh finds the same displacements of phase for the blue as for the green cadmium line,[1] whence we might conclude that for the green line the limit of penetration is already reached. There is, however, evidence in favor of the view that the blue line possesses peculiarities which must disturb the measurements. I have in fact been obliged to conclude that there are some phenomena which at present are unknown to me, and I was unable to determine the correction ϵ in the same way as for the red line. However, I reserve it for a later test. I must content myself with completing the lower branch of the curve in Fig. 5 from the values of Perot and Fabry.

It is my purpose to carry out the work of establishing normals as rapidly as possible, and it is my intention to employ the method adopted by Perot and Fabry. By this method the light is dispersed after its passage through the silvered air-stratum, and we then get a spectrum the lines of which are composed of a number of small arcs which correspond to the interference rings. In this way with one process we obtain a large number of lines on the photographic plate which can then be measured just as are the single rings.

[1] He assumed for the red line $\epsilon = 0$.

ON THE CONSTANCY OF WAVE-LENGTH OF SPECTRAL LINES

By H. KAYSER[1]

An extensive literature has already grown up on the question whether the wave-lengths of spectral lines are invariable or whether they depend on the mode of production of the spectrum, whether the density of the vapor has any effect, etc. I have just received a paper by Exner and Haschek,[2] who have been the principal representatives of the assumption of variability of wave-lengths, in which the authors attempt to add new evidence for their view. The importance of this question in terrestrial and astronomical spectroscopy leads me to make some remarks on the subject. The gentlemen wish to establish a case on three measurements of the spectrum of lanthanum made by different students in my laboratory, in which as a matter of course differences of wave-length occur amounting to several hundredths of an Ångström unit. These differences Exner and Haschek seek to interpret as proof of the variability of the wave-lengths.

This explanation is in my opinion incorrect. A principal reason for the differences appears to me rather, to lie in the errors of the standards from which the wave-lengths were determined. I have previously referred to this effect, stating,[3] "I am convinced that the much larger differences (than several thousandths of an Å) which different observers obtain for the same line are due to the fact that they depart from different standards, which do not agree with each other."

It is true that the three gentlemen all took their standards from my table of the iron spectrum or from Rowland's tables for the Fraunhofer lines; but they took different lines as standards, whereby, in view of the inaccuracy of the standards, errors of 0.02 Å can easily arise. This very fact that with the same standards an accuracy of a few thousandths Å is attained, while with different standards only as many hundredths of a unit, led the International Solar Union to

[1] Translation from the *Zeitschrift für wissenschaftliche Photographie*, 5, 304–308, August 1907.

[2] *Sitzungsberichte der Wiener Akademie*, 116, II*a*, 323–341, 1907.

[3] *Zeitschrift für wissenschaftliche Photographie*, 2, 50, 1904.

place upon its programme the more precise determination of the standards as one of the most pressing problems.

A comparison of the series of measures shows clearly that the insufficiency of the standards is principally to blame. My iron standards were produced by the adjustment of many errors in Rowland's values, and they therefore agree very much better among themselves than Rowland's solar standards. Therefore in the region from λ 2200 to λ 4500, in which my standards were employed, the differences must be smaller than for greater wave-lengths. This is confirmed as follows: In the first region Kellner measured 151 lines, in the second 88 lines. Differences between him and Wolff in amounts of 0.06 and 0.05 occur, in all, four times, and these only in the second region. The difference 0.04 occurs seven times in the second region, but only three times in the first, in spite of the twofold number of lines in the first region. The difference of 0.03 occurs only half as often in the second region; and only the small differences of 0.01 and 0.02 are uniformly distributed over the two regions.

In addition to this principal cause of the differences, errors of measurement also surely occur for some of the lines. Practice is necessary for correct measurement, particularly for lines that are not quite sharp, and the measures referred to here were by beginners. Individual errors will always arise, even if I also check the measures and convince myself by tests of their general correctness.

While I differ from Messrs. Exner and Haschek in the explanation of these differences of measurement, I cannot see in the numerical values any evidence whatever for a displacement toward the red. On the contrary it is easy to see again here that errors of the casually selected standards sometimes make the measurement larger and sometimes smaller. I compare here only the longer waves according to Wolff and Kellner: from λ 447 to λ 467 the values of the former are all larger, from λ 469 to λ 510 smaller, from λ 510 to λ 516 larger, from λ 516 to λ 526 again smaller, from λ 526 to λ 538 larger, from λ 545 to λ 551 smaller, and then about equal to the end of the measurements. We see from this that the differences always cover larger portions of the spectrum, as would be the case in inaccurate standards. The correction curve of the one measurement with respect to the other would be a sort of sine curve, and no conclusions of any sort

are justified from these figures as to a displacement toward the red or toward the violet.

Further proofs of the constancy of wave-lengths have happily been brought out very recently which could not at the time have been known to Messrs. Exner and Haschek. The condition set by the Solar Union that a new system of standards should be produced, which should all be correct within a few thousandths of a unit, obviously could be carried out only if the wave-lengths are invariable. Therefore this fact had to be tested first. At the meeting of the Union in Paris in May, Professor Ames was able to communicate the fact that Dr. Pfund had made experiments in his laboratory with the interferometer which proved that the wave-lengths are precisely the same, regardless of whether the spectrum was produced in the spark or in the arc, at atmospheric pressure or in a vacuum, of pure metals or of an alloy or salts. This was true without exception for all the elements investigated. Professor Fabry declared that his experiments had yielded precisely the same result. Inasmuch as the most precise method which we have was employed here, we must regard these experiments as decisive, and consider that the question of the constancy of the wave-lengths is finally settled.

In the second part of their paper Messrs. Exner and Haschek discuss another phenomenon which to me does not seem quite in place there, or at least alters their position in comparison with their former view. I am. probably not wrong in assuming that the gentlemen herewith abandon a part of their former view. They assumed formerly that the lines were displaced continuously and accordingly to law with the density of the vapor; indeed a quantitative analysis was to be based on this displacement. Now they say that many lines are formed of numerous components and under various forms of excitation of the spectrum, one or the other of these components may become stronger; the center of gravity of the combination might then be displaced in the grating spectrum, in which the line is not resolved. It is quite clear, and was long ago pointed out, that this case is possible and that in this sense variable lines can exist; but it is equally obvious that this could never occasion a continuous displacement proportional to the density of the vapor. Furthermore, it would be just as probable that the component line toward the violet should be

the stronger as the one toward the red. It may have been merely a matter of chance if Exner and Haschek observed components to be stronger only on the red side when working with an inadequate echelon.

It is further to be remarked that the number of lines resolved by the echelon into components is vanishingly small in comparison to the number of simple lines, if we may judge from the little we thus far know on this subject—hardly more than one investigation, by Nutting, can be mentioned.

It follows from this that that sort of variability of wave-length may indeed theoretically occur, but only for a small number of lines; and that this variability has nothing to do with the continuous displacement previously asserted to exist. I also know of no case where an actual displacement could be proven from this cause. Only in the case of the cadmium line λ 5086, which Exner and Haschek also mention, has a variability of the components been safely established, by the observations of Hamy and Fabry. In spite of this, this line is an excellent standard of invariable wave-length.

But if we assume that actual and marked variations of components frequently occur, then the result is simply what Eder and Valenta and I have asserted from the beginning: the wave-length remains constant *if correctly measured;* that is, if the position of the principal component, of the maximum, is determined; and this is equally true for composite lines and for lines unsymmetrically widened.

I am glad to see from Exner and Haschek's paper (p. 337) that they are now of this same opinion; for, in withdrawing their assertion that actual displacements are involved, they actually recognize that only apparent displacements are in question and that the wave-length remains unchanged with a correct measurement.

They are confirmed in this view by the above-mentioned results of Ames and Fabry, and herewith no difference of opinion may be expected to continue regarding this question, which has been decisively settled by experiment.

BONN, GERMANY
July 1907

Reviews

A General Catalogue of Double Stars within 121° of the North Pole. By S. W. Burnham. Published by the Carnegie Institution of Washington, 1906. Price, $14.00.

The monumental works in any field of science are not numerous. Two have now appeared in the department of double-star astronomy: Struve's *Mensurae Micrometricae*, bearing the date 1837, and Burnham's *General Catalogue*, the title of which appears as the heading of this article. It is true that many great works on double stars have been published, but these two stand above the others in comprehensiveness and enduring qualities.

The first general catalogue of double stars was printed in 1820 by Wilhelm Struve, enumerating the 795 objects of this class then known from the north celestial pole to 20° south declination. Seven years later, after his extensive exploration of the northern heavens, resulting in a vast number of discoveries, Struve published his *Catalogus Novus Stellarum Duplicium et Multiplicium*, listing 3,112 objects from the north pole to 15° south declination. This became Struve's working programme and after he had measured all the stars in it which he deemed worthy of retention, he printed his measures in *Mensurae Micrometricae*, a work which summed up to the time of its publication all that was best in the observational data respecting the stars to which it relates. Moreover, it was a finished work, which at once became an example and guide, giving direction and character to double-star investigations, which have continued in force to the present.

However thoroughly we may sum up the accomplishments in a large department of science to a given epoch, the subject does not rest, but new results continue to appear, making formidable additions to those already collected. Thus, while Struve was making the observations which are published in *Mensurae Micrometricae*, Sir John Herschel was exploring the skies of both hemispheres, making many discoveries, which he announced from time to time in various catalogues, which eventually included more objects than had been registered by Struve. A few years later, in 1843, Otto Struve's *Pulkowa Catalogue* appeared, and after that, although observations continued to be made in great numbers, the discovery of new

pairs rested for a space of nearly thirty years. It was revived by Professor Burnham, at Chicago, experimenting at first with a little instrument just good enough to make something better desirable. Fortunately a better instrument was soon acquired, and then he startled the astronomical world with the revelation that the explorations of the Herschels and the Struves were not complete, but that virgin fields remained even to the possessor of a six-inch refractor.

Burnham had not used this instrument long before he felt the need of a complete and reliable list of the double stars then known, and to supply this want he began to collect the material which has grown into the volumes before us. In the introduction he tells us how it came about. The small refractor, from the beginning, was used almost entirely for the observation of double stars. Objects were constantly found with it which could not be identified in any of the books at hand for reference. At that time there were few books in Chicago relating to double stars, and no complete catalogue existed of those then known. To meet his needs he began to form a manuscript catalogue from the books that were accessible to him. Observatories were visited and their libraries consulted; books were borrowed and their contents noted; books and memoirs were purchased, making the beginning of a library pertaining to this subject that has become practically complete. The manuscript catalogue formed at the outset at so great a cost of time and labor has been kept continuously posted to date, by the addition of all new stars and new measures from current publications. In order to make room for new material a second manuscript edition eventually became necessary, and still later a third, which finally passed into the hands of the printer, and now appears in finished form.

This work is in two parts. Part I, which is complete in itself, contains the *Catalogue* proper, enumerating 13,665 double and multiple stars from the north celestial pole to 31° south declination. This fills 274 large pages, including an appendix of 18 pages giving the double stars announced from the Lick Observatory while this work was passing through the press. The introduction, devoted mainly to a brief description of the volume; and the indices and precession tables, fill 55 pages additional. Part II contains the *Notes to the Catalogue.* These fill 838 closely printed quarto pages.

Part I is in tabular form, with eleven columns to the page. The stars are arranged in the order of their right ascensions and are numbered consecutively. These reference numbers are given in the first column. The second column contains the name of the star according to its usual desig-

nation in this department of astronomy; and the third, its name or constellation letter or number, or failing these, its number in some standard catalogue of stars. The fourth and fifth columns contain the right ascension and declination for the epoch 1880, an epoch which was selected for this work before any of the *A. G.* catalogues were printed. The data given in the remaining columns are the position angle, distance, and epoch of the earliest reliable measures; the magnitudes of the components; indication of the observers and the number of nights on which measures were made; and brief notes, usually relating to notation and colors of components and such references as may be compressed into a short line. Many double stars have to the present but a single set of measures. This is especially so for many of the pairs recently discovered. Often all data of interest respecting such a star may be given in a single line, and such pairs are not always mentioned in the notes in Part II.

The notes in Part II are given in the order of the stars in Part I; that is, in the order of their right ascensions, which, for convenience of reference, are here placed in the margins of the pages. Each note is preceded by the reference and double-star numbers of the pair, and also, when it has them, by the star's name and synonym. The notes are reduced to a very compact form, giving in a few words an outline of the star's history, selected measures for various epochs, conclusions respecting relative and proper motions, and, what is most valuable, complete references to all published observations. These are the data most useful for general purposes and they are presented in a form above criticism. Diagrams often accompany the notes to the binaries and proper motion stars, especially when the change in the relative situations of the components has been considerable. These diagrams, by graphically picturing the motion, render it the less necessary to quote long lists of measures, and the author has elected to give these rather sparingly. On some accounts it might have been better to have quoted larger numbers of observations, enough, when they are available, to enable one to form an independent opinion as to the character of the motion of any given pair. Now one has generally to rely upon the author's conclusion, or turn to the original sources, which may not be more accessible to a given investigator than they were to the author when he began this work thirty-seven years ago.

Except in the case of *β Delphini*, the only element of the orbits of the binaries quoted is the periodic time. It is to be regretted that the other elements are not also given, for they too are necessary to the making of exact comparisons between observed and computed places.

This work is not a mere compilation, as might, perhaps, be inferred

from what precedes. On the contrary, in its presentation of new and important facts, it is a great contribution to knowledge. Its highest merit resides in its reliability, which could not have been secured by consulting publications alone. For many years Professor Burnham has been a most industrious observer, having had at his command at various times, some of the largest and best telescopes of the world, among them the large refractors of the Washburn, Dearborn, Lick, and Yerkes observatories. With each of these instruments he has set at rest many questions which could only be answered by an appeal to the sky, and then oftentimes only by the faithful following of particular stars through many years.

Professor Burnham has endeavored to bring the histories of all the double stars in this work as nearly up to date as possible, and this has necessitated the re-observation of the neglected pairs. For some years he has devoted himself unremittingly to this task, and in these volumes he has given us for the first time the mean results of several thousand observations, made to fill this special need. When we look over the record and remember that these new measures were obtained by observing on two nights only per week, we wonder at his accomplishment.

Among the features which increase the value of this as a reference work, are the tables in Part I, following the introduction. Here, in compact form, the double stars discovered by modern observers are conveniently indexed, enabling any pair to be readily found. Tables follow, giving a provisional grouping of those stars which have given evidence of their character by means of their motions. Precession tables are also provided, which will be very useful in comparing the places of the stars at different epochs, as may be necessary in verifying identifications.

So meager are the data to the present, even when collected as given in this work, that it is not possible to make more than a beginning in the separation of the double stars into the different classes to which they belong, putting the binaries in one group, those whose components have a common proper motion in another, and so on. According to Professor Burnham's tables, just mentioned, the number of objects in each class is as follows:

Binaries with computed orbits	88
Binaries without computed orbits	94
Stars probably binary	112
Stars of the type of *61 Cygni*	38
Stars with common proper motion	579
Rectilinear motion	387
Total	1,298

If this classification were made by another person, the numbers would doubtless be altered slightly, by the transfer of certain stars from one group to another. For example, I should place *61 Cygni* among the stars probably or certainly binary. But the general result would remain the same. The table is an impressive commentary on the slowness with which the substantial facts concerning the apparent movements of the stars are obtained. Out of the 13,665 double stars enumerated in this great catalogue, and of which roughly 6,000 have been known for more than sixty years, only 88 are classed as binaries with orbits computed, and for more than half of these the elements are so uncertain that little reliance may be placed in them. It is even doubtful whether some of them are binaries. Thus, an orbit has been computed for λ *Cygni*, but so far as may be judged from the observations, this pair is as likely to prove a case of rectilinear motion as a binary combination.

Further, from the table above it will be seen that less than 10 per cent. of the stars which have been catalogued as double have moved sufficiently since their first observations were obtained to enable us to form an opinion respecting the character of their motions, and exclusive of the pairs whose components have a common proper motion, only 2½ per cent. are as yet known to be binaries. That the number of proven binaries is so small, doubtless results from the too generous inclusion of wide pairs by the earlier observers, and to the fact that nearly one-fourth of all the stars listed are recent discoveries, which have been measured at one or two epochs only. The discoveries of the past decade include a large majority of the close double stars, and when these are measured anew, at intervals sufficiently separated, the percentage of established binaries will doubtless be materially increased. Here, as in other departments of this subject, observation is the way of progress, and in this Professor Burnham's work will be a powerful aid, supplying what has hitherto been wanting, the means of judiciously selecting an observing programme.

The need of a general catalogue of the known double stars, which Professor Burnham experienced thirty-seven years ago, has been felt by every worker in this field who has passed beyond the boundaries of the subject and attempted to add material of value to this department of knowledge. The exigencies of the situation have imposed upon some of us the necessity of forming manuscript catalogues of the known double stars to facilitate our own investigations. Thus, when the systematic survey of the stars to the 9.1 magnitude was begun in 1899 at the Lick Observatory, I found it necessary to search through hundreds of publications, as Professor Burnham had done, and construct manuscript lists of

the double stars contained in them. In doing this my labor was less arduous than Professor Burnham's, for I did not attempt to collect all the published observations of the stars, and moreover, I had at my command what he did not have at the beginning, a large astronomical library, with many references in this particular department. Nevertheless, the labor involved in this, and the making of nearly ten thousand observations, and in the telescopic examination of many thousands of stars besides, was sufficient to give me an appreciation of the magnitude of his accomplishment. The production of his *General Catalogue*, from whatever standpoint it may be viewed, must be regarded as one of the great, single-handed achievements in astronomy.

W. J. HUSSEY

ANN ARBOR, MICH.
September 1907

Stereoskopbilder vom Sternhimmel. 1. Serie. Von MAX WOLF. Leipzig: J. A. Barth, 1906. 5 Marks.

This little portfolio of photographic prints embraces a most interesting series of twelve celestial "stereograms" arranged in the following order: 1, variable star *R Coronae;* 2, *Saturn* and two of his moons; 3, asteroid trail—*Svea*, No. 329; 4, meteor trail; 5, 6, 7, three views of Comet *b* 1902; 8, star showing large proper motion; 9, *Andromeda* nebula; 10, *Orion* nebula; 11, lunar *Apennines;* 12, region around the lunar crater *Albategnius*. Accompanying each print is a double page of descriptive matter.

Examination of the views shows that not all are true stereograms, as it is obviously impossible to obtain the effect of relief upon such objects as the *Orion* or *Andromeda* nebulae; this is remarked upon, however, in the letter-press.

If any adverse criticism could be made of this generally excellent series, it might be that those of the moon (from the negatives of Loewy and Puiseux) are the least pleasing from an optical standpoint, while it might be objected that Nos. 5, 6, 7, 11, and 12, have suffered such enlargement as to render the silver grain particles objectionably apparent. In Nos. 9 and 10 an improvement could have been effected by judicious chemical reduction of the negatives, whose "contrast" is fatal to the portrayal of detail.

Considered as a whole, the series is good, and should meet with prompt appreciation and a ready sale.

R. J. W.

A GENERAL INDEX TO THE ASTROPHYSICAL JOURNAL

The preparation of an index to the first twenty-five volumes of this Journal, covering the twelve and one-half years from January 1895, to June 1907, is now under consideration. Such an index would doubtless prove of great convenience to the workers in astrophysics and to libraries. The possibility of its publication will depend upon the number of advance orders received. If 200 subscriptions are obtained, the index can probably be issued; if 300 advance orders should be given, the work will certainly be undertaken, with the expectation of its publication in the winter of 1907,–8 and the price will probably be $1.50.

All subscribers and librarians who would purchase such an index, if issued, are therefore requested to notify the publishers at once by postcard of the number of copies for which they will subscribe.

Address, The University of Chicago Press, Chicago, Illinois, U. S. A.

NOTICE

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

In the department of *Minor Contributions and Notes* shorter articles will generally be placed and subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right, unless the author requests that the reverse procedure be followed.

Accuracy in the proof is gained by having manuscripts type-written, provided the author carefully examines the sheets and eliminates any errors introduced by the stenographer. It is suggested that the author should retain a carbon or tissue copy of the manuscript, as it is generally necessary to keep the original manuscript at the editorial office until the article is printed.

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Authors will please carefully follow the style of this *Journal* in regard to footnotes and references to journals and society publications.

Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

If a request is sent *with the manuscript*, one hundred reprint copies of each paper, bound in covers, will be furnished free of charge to the author. Additional copies may be obtained at cost price. No reprints can be sent unless a request for them is received before the JOURNAL goes to press.

The editors do not hold themselves responsible for opinions expressed by contributors.

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THE

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SPECTROGRAPHIC OBSERVATIONS OF THE ROTATION OF THE SUN[1]

BY WALTER S. ADAMS

The spectroscopic study of the rotation period of the sun's reversing layer has hitherto been confined to visual measures of lines in the less refrangible part of the spectrum. In 1890 Dunér published his classical research upon the subject, including in his discussion results covering the period of three years from 1887 to 1889. Later he supplemented these values with observations made during the years 1899, 1900, and 1901.[2] During the last of these years Halm began the same investigation at Edinburgh, using a fixed horizontal spectroscope and a heliometer to bring the images of the opposite limbs of the sun upon the slit of his instrument. He has since published determinations extending up to 1906[3] and his measures indicate results of the highest accuracy, the probable error for a single observation falling considerably below that of Dunér. In both of these investigations the lines employed were the same, and consisted of a pair of iron lines in the red region of the spectrum having the wavelengths 6301.72 and 6302.71 on Rowland's scale. The desirability of extending the research to other elements and of employing the obvious advantages of the photographic method as soon as suitable apparatus was available was early realized by Professor Hale at this

[1] *Contributions from the Solar Observatory*, No. 20.

[2] *Astronomische Nachrichten*, 167, 167, 1905.

[3] *Idib.*, 173, 273–295, 1907.

observatory, and it was at his suggestion that this investigation was commenced.

It is clear that a satisfactory photographic study of the displacements at the sun's limb requires a solar image of considerable size combined with a spectrograph of high dispersion, and sufficient focal length to give full photographic resolution. Both of these are available with the Snow telescope. The concave mirror of this instrument forms an image upon the slit of the spectrograph about 6.7 inches (17.0 cm) in diameter. The spectrograph is of the Littrow, or auto-collimation, type, with a lens 4 inches (10.2 cm) in diameter and 18 feet (5.5 m) focal length employed in conjunction with a plane grating of the same aperture. This grating, which by the kindness of Professor Frost of the Yerkes Observatory has been loaned to the Solar Observatory, is one of the early Rowland gratings, and has 14,438 lines to the inch (570 lines to the mm). It is exceptionally bright in both the third and fourth orders, and gives excellent definition in spite of the great focal length of the spectrograph. The spectra used in this investigation have all been taken in the fourth order, the advantages of the larger scale more than offsetting the greater width of the spectrum lines. The linear scale of the instrument in this order at λ 4200 is about 1 mm = 0.71 Ångström unit.

The apparatus used to bring the opposite limbs of the sun together on the slit is an adaptation of that first employed by Langley and afterward used by Dunér in his well-known investigations. A pair of small diagonal prisms is mounted on each of two rotating brass arms. The first of these prisms is placed at the outer end of the arm, its mean distance from the center of rotation corresponding to the mean radius of the sun's image, and is capable of adjustment along the arm to correspond with the varying size of the image. A second prism, which receives the beam from the first and reflects it upon the slit, tapers at the end to a width of about 0.5 mm, and is mounted with a point slightly inside the center of this end immediately above the center of rotation of the brass arm. The distance between the edges of the prisms on the two arms is about 0.25 mm, which accordingly represents the distance on the photographic plate between the spectra of the two opposite limbs. The two arms are rotated on a brass frame, and are provided at the ends with pointers by means of

which readings are made on a silver position-circle, graduated to half-degrees, and capable of being estimated to tenths. The whole apparatus is mounted upon a brass casting which rests upon a large bracket below the slit of the spectrograph, its position being accurately defined by two taper pins which enter this bracket.

In adjusting this instrument previous to beginning upon the series of observations, great care was taken to secure equal and uniform illumination of the grating surface from the two sets of prisms at all position angles. The simplest method of doing this was to occult the images of the two limbs in succession, and to examine visually from the position of the photographic plate the character of the illumination of the grating. With a narrow slit and comparatively weak illumination this method gives good results. It has, however, been supplemented with photographic tests, the illumination of the collimating lens being photographed on sections of sensitized paper pressed against the rear surface of its cell. The adjustment once made, it has been found necessary to change it on only one occasion, when, owing to a fracture, one of the small diagonal prisms had to be replaced. Since the ratio of aperture to focal length is 1 to 54 in the case of the collimating lens, and 1 to 30 for the image-forming telescope, it is clear that the margin of safety is considerable. It has, however, been the practice to examine visually the character of the illumination previous to each exposure; and it is needless to add that a further valuable check is furnished by the relative density of the pair of spectra upon the photographic plate.

The procedure followed in making the observations has been as follows. The rotation attachment is set in place upon the bracket beneath the slit of the spectrograph, and the image of the sun focused upon the position circle at its edge. The clock driving the coelostat is then stopped, and a spot or other well-defined point upon the sun's surface is allowed to transit across the circle, readings being made at both points of crossing. The mean of three or four such observations, which rarely show a range of more than $0^\circ.3$, is used as the line of reference for the determination of the heliographic positions. The pointers on the arms carrying the diagonal prisms are then set at the proper reading of the position circle, the character of the illumination of the grating surface is examined, and the exposure made. The

position angle is then changed and the process repeated. On the majority of the plates an exposure has been made for every 15° of latitude between 0° and 75°. This has been done in order to obtain results directly comparable with those of Dunér. A considerable number of intermediate points have been used, however, particularly in high latitudes. At the close of the set of exposures a second series of transits of the spot across the position circle is taken.

The selection of the region of the spectrum most suitable for the work has given considerable difficulty on account of the necessity of securing a sufficiently varied list of lines within a comparatively short extent of spectrum. The portion finally chosen is that extending from λ 4190 to λ 4300. This includes a part of the extremely rich G region, and has the additional advantage of containing the head of the violet carbon fluting, some lines of which it is most desirable to use in the investigation. Another determining feature was the fact that the maximum of sensitiveness of the Seed "process plate" lies not far from this point. This plate has always proved very satisfactory for spectrum work in the blue and violet regions, showing a fine grain and excellent contrast, while at the same time it is appreciably more rapid than the ordinary transparency or lantern-slide plates. The following list of lines was finally adopted:

λ	Element	Intensity	Remarks
4196.699	*La*	2	Much weakened at limb.
4197.257	*C*	2	Slightly weakened at limb
4203.730	*Cr*	2	Strengthened and widened at limb
4209.144	*Zr*	1	Weakened at limb
4216.136	*C*	1	Weakened at limb
4220.509	*Fe*	3	Slightly strengthened at limb. Chromospheric line
4232.887	*Fe*	2	Much strengthened at limb
4257.815	*Mn*	2	Probably weakened at limb
4258.477	*Fe*	2	Much strengthened at limb. Much strengthened in sun-spots
4265.418	*Fe*	2	Slightly weakened at limb
4266.081	*Mn*	2	Perhaps weakened at limb
4268.915	*Fe*	2	Slightly weakened at limb
4276.836	–*Zr*	2	Weakened at limb
4284.838	*Ni*	1	Slightly weakened at limb
4287.566	*Ti*	1	Slightly strengthened at limb. Strengthened in sun-spots
4288.310	*Ti, Fe*	1	Widened at limb
4290.377	*Ti*	2	Slightly weakened at limb. Enhanced line of *Ti*
4290.542	*Fe*	1	Probably weakened at limb
4291.630	*Fe*	2	Much strengthened at limb. Strengthened in sun-spots
4294.936	*Zr*	2	Probably weakened at limb

At the time at which this list of lines was selected the remarkable differences between the spectrum of the center and that of the limb of the sun were not known.[1] It was, however, noted that the lines upon the plates appeared in general rather diffuse and "matt," to use the German expression, and the exposure times were much longer than was to be expected from exposures made on the disk of the sun without auxiliary apparatus. A part of this effect was ascribed to the fact that the light was obliged to traverse some 3 inches (76 mm) of glass in passing through the diagonal prisms. The true cause, however, was not understood until the investigations of Professor Hale and myself showed the radical difference in character and intensity of the spectra of the two parts of the sun's image.

The necessity for selecting only the lines best adapted for measurement has, of course, excluded many interesting lines from the above list, but those given may be regarded as reasonably comprehensive as regards the elements represented, and their behavior at the limb and the center of the sun. The line due to lanthanum is included on account of the high atomic weight of this element, and a similar reason holds for the three lines of zirconium, though in less degree. Carbon is of great interest on account of its position in the chromosphere, and is represented by two lines. The remaining lines are divided among the more important solar elements, iron naturally occupying the most prominent position.

The series of plates amounting to 44 in number included in this discussion was begun in May 1906, and extends to June 1907, a period of nearly fourteen months. Though not distributed uniformly throughout this time they cover the period fairly well with the exception of the interval from July to October, 1906. During these months it was not possible to secure observations on account of the breaking of one of the small central diagonal prisms. In selecting the plates to be measured, only such were chosen as were taken on days when the sky was suitably transparent, and no daylight spectrum was superposed upon the spectra of the two limbs. This point was usually tested by direct visual observation, in the same way as was done by Halm in his series of visual measures in the less refrangible region of the spectrum.

[1] Hale and Adams, *Contributions from the Solar Observatory*, No. 17; *Astrophysical Journal*, 25, 215–225, 1907.

The computation of the heliographic latitudes of the observed points has been made for the most part with the use of De La Rue's reduction tables. These give with the sun's longitude as an argument the position angle of the sun's axis in reference to the north point, and the heliographic latitude of the earth. Since we know the position-circle reading of the point under observation as well as that of the east and west line, the position angle from the north point is known at once, and the computation of the latitude is made simply. For setting the position circle during the observations the table for the position angle of the sun's axis given in the *Companion to the Observatory* has been found very useful. The angle, by the secant of which it is necessary to multiply the observed velocities in order to correct for the departure of the sun's pole from its visible edge, has been taken from the table given by Dunér, except for high latitudes, in which case it has been computed directly. The further correction to be applied for the distance inside the sun's edge from which the light which passes through the slit of the spectrograph has been taken, is found as follows. With the almanac value of the sun's diameter and the scale-setting of the concave mirror of the telescope the value of the linear diameter of the sun's image is computed. The distance between the small windows through which the diagonal prisms receive the light being accurately known, the factor required is readily derived. In practice it has been found preferable to change this distance occasionally rather than to attempt to keep at a fixed distance from the sun's edge as the diameter varied.

The greater part of the plates have been measured by Miss Lasby of the Computing Division upon the 150 mm measuring machine built by Toepfer. The screw of this instrument has a pitch of 0.5 mm, and the divided head may be read to 0.5 μ. A series of measures upon a fixed distance ruled on a glass plate for every other ten revolutions of the screw from 10 to 280 showed remarkably small periodic errors. At a maximum these amount to 0.3 μ which is much below the limit of accuracy of measurement of spectrum plates. The errors of run of the instrument do not, of course, need to be considered in small differential measurements of this sort. A few of the plates have been measured upon a small comparator built by Gaertner of Chicago. An investigation of the screw of this machine has indicated periodic

errors considerably larger than those of the Toepfer instrument, but they still fall below the errors of measurement and may be neglected.

An important consideration to be borne in mind in the measurement of the plates is that of the inclination of the cross-wire in the eye-piece of the measuring instrument. It is evident that unless this coincides accurately with the inclination of the spectrum lines error will be introduced into the measured displacements, since reversing the plate in the ordinary way does not affect the position of the wire in this regard. The objections to attempting to correct by making the second measurement through the glass are obvious. Accordingly, the following procedure has been followed. A solar spectrum has been photographed with a very long slit, having a horizontal line running through its center due to a fine wire stretched across the slit. This plate is used as a standard, and the vertical wire in the eye-piece of the measuring machine is carefully adjusted until it is accurately parallel to the spectrum lines after the plate has been lined up in the usual way with the aid of the horizontal line. It is evident that with the wire adjusted by the use of these long lines any error in its inclination with reference to the very short lines of the rotation spectra must be quite negligible. After this adjustment has been made the cross-wire of the measuring instrument is clamped in position. A change of position of the grating or any inclination of the slit of the spectrograph would, of course, necessitate a new adjustment of the cross-wire, but this has occurred on only one occasion.

In the conversion of the measured displacements into radial velocity use has been made of a small table which combines into one factor for each line the various reduction factors which it is necessary to employ.

It is of course impossible to give the details of the individual plates within the limits of this article. Accordingly, it has seemed best to include two tables of summaries, the first giving the values of the velocities for each plate derived from a mean of all the lines, and the second the value for each line derived from a mean of all the plates. Both the linear and the angular velocities are reduced to the sidereal period of rotation.

The following table furnishes a summary of the results of the separate plates for each latitude. The values given are the means of all the lines measured.

TABLE I

Number of Plate	Date 1906	Number of Lines	ϕ	v km	Number of Plate	Date 1906	Number of Lines	ϕ	v km
ω 3	May 3	20	9°9	2.012	ω 25	June 15	20	60°0	0.848
			24.8	1.803				75.0	0.414
			39.8	1.414	ω 26	June 16	20	0.2	2.088
			54.7	0.995				15.0	1.973
			69.6	0.584				30.0	1.636
			83.6	0.169				44.9	1.271
ω 6	May 8	19	10.7	2.026				59.9	0.852
			25.7	1.789				74.9	0.442
			40.6	1.390	ω 27	June 16	20	0.0	2.077
			55.6	0.981				15.0	1.959
			70.5	0.575				30.0	1.656
			84.6	0.146				45.0	1.263
ω 8	May 19	19	0.8	2.063				60.0	0.862
			15.6	1.969				74.9	0.452
			30.6	1.688	ω 30	Oct. 19	20	0.0	2.109
			45.5	1.317				14.9	1.966
			59.2	0.944				29.8	1.695
			75.4	0.433				44.8	1.293
ω 19	June 12	20	0.0	2.063				59.6	0.876
			15.0	1.946				74.1	0.488
			30.0	1.673	ω 31	Oct. 19	20	0.0	2.110
			45.0	1.271				15.0	1.974
			60.0	0.862				29.9	1.698
			75.0	0.446				44.9	1.312
ω 20	June 12	20	0.0	2.071				59.8	0.898
			15.0	1.932				74.2	0.498
			30.0	1.659	ω 35	Nov. 11	20	0.5	2.056
			45.0	1.262				74.2	0.467
			60.0	0.856	ω 36	Nov. 11	20	0.5	2.078
			75.0	0.439				14.4	1.977
ω 21	June 12	20	0.0	2.060				29.4	1.683
			15.0	1.939				44.4	1.277
			16.0	1.939				59.3	0.889
			30.0	1.664			19	74.2	0.488
			45.0	1.267	ω 37	Nov. 11	20	0.5	2.082
			60.0	0.849				14.4	1.975
			75.0	0.444				29.4	1.689
ω 23	June 15	20	0.1	2.056				44.4	1.276
			15.1	1.937				59.3	0.881
			30.1	1.667				74.2	0.472
			45.1	1.252	ω 38	Nov. 11	20	0.5	2.077
			60.1	0.845				14.4	1.958
			75.0	0.430				29.4	1.670
ω 24	June 15	20	0.0	2.071				44.4	1.273
			15.0	1.939				59.3	0.871
			30.0	1.672				74.2	0.470
			45.0	1.265	ω 39	Nov. 11	20	0.5	2.081
			60.0	0.858				14.4	1.956
			74.9	0.440				29.4	1.677
ω 25	June 15	20	0.0	2.067				44.4	1.281
			15.0	1.961				59.3	0.882
			30.0	1.656				74.2	0.473
			45.0	1.269	ω 39½	Dec. 18	20	1.2	2.099

TABLE I—*Continued*

Number of Plate	Date 1906–7	Number of Lines	ϕ	v km	Number of Plate	Date 1907	Number of Lines	ϕ	v km
ω 39½	Dec. 18	20	15°.2	1.969	ω 61	Feb. 28	16	44°.0	1.261
			30.2	1.696	ω 62	Feb. 28	20	6.0	2.041
ω 40	Dec. 18	20	0.2	2.085				7.9	1.995
			0.2	2.095				15.6	1.944
			15.2	1.962				22.5	1.786
			15.2	1.962				30.2	1.652
			30.2	1.685				38.1	1.510
			30.2	1.689	ω 63	Feb. 28	20	7.2	2.035
ω 41	Dec. 18	20	0.2	2.087				20.6	1.841
			0.2	2.073				28.2	1.672
			15.2	1.950				35.1	1.533
			15.2	1.952				50.7	1.055
			30.2	1.691				43.8	1.280
			30.2	1.679	ω 64	April 7	20	77.5	0.359
ω 46	Dec. 18	20	44.4	1.285	ω 67	April 7	20	77.5	0.360
			44.4	1.282	ω 68	April 7	20	77.5	0.365
			44.4	1.282	ω 69	April 7	20	77.5	0.365
			59.4	0.877	ω 81	April 22	20	67.2	0.642
			59.4	0.868				67.2	0.635
			59.4	0.871				72.5	0.485
ω 48	Dec. 18	20	35.4	1.532				72.5	0.483
			35.4	1.509				79.5	0.326
			44.4	1.294				79.5	0.321
			51.9	1.071	ω 83	May 10	20	63.5	0.749
			51.9	1.076				63.5	0.747
			59.4	0.881				74.4	0.441
	1907							74.4	0.437
ω 50	Feb. 3	20	7.1	2.009				79.2	0.311
			23.0	1.828				79.2	0.303
			37.9	1.510	ω 85	May 30	20	63.8	0.723
			53.7	1.002				63.8	0.728
			69.2	0.596				74.8	0.442
			77.5	0.325				74.8	0.441
ω 55	Feb. 15	20	7.4	2.046				59.8	0.304
			22.3	1.838				79.8	0.306
			38.2	1.458	ω 86	May 31	20	14.8	1.967
ω 56	Feb. 15	20	7.4	2.010				29.8	1.663
			22.3	1.846			19	44.8	1.298
			38.2	1.455			20	64.1	0.750
			53.9	1.045				76.1	0.392
			69.4	0.608				81.1	0.267
ω 60	Feb. 28	20	6.9	2.041	ω 87	June 22	20	8.1	2.024
			6.9	2.045				23.1	1.794
			20.8	1.837				38.6	1.407
			28.4	1.676				52.1	1.053
			35.3	1.510				52.1	1.048
		20	43.6	1.295				59.1	0.857
			50.7	1.088	ω 88	June 22	20	8.1	2.036
ω 61	Feb. 28	18	59.8	0.831				23.1	1.783
		17	65.6	0.676				38.6	1.406
		18	65.6	0.676				52.1	1.063
		17	59.9	0.824				52.1	1.062
		18	50.9	1.102				59.1	0.851

TABLE I—*Continued*

Number of Plate	Date 1907	Number of Lines	ϕ	v km	Number of Plate	Date 1907	Number of Lines	ϕ	v km
ω 89	June 22	20	8°.5	1.990	ω 90	June 22	20	35°.4	1.440
			23.5	1.787				54.5	1.006
			39.0	1.400				53.0	1.063
			52.5	1.077				64.7	0.721
			52.5	1.069	ω 91	June 23	20	6.9	2.011
			59.5	0.856				21.9	1.780
ω 90	June 22	20	6.9	2.044				37.4	1.423
			21.9	1.791				53.0	1.064

The results given in this table have been grouped into mean positions for twelve latitudes, and a summary of the values for these latitudes is found in the latter part of the discussion. In Table II, immediately following, the results are given for the individual lines of the list, the number of plates included under each mean latitude being indicated in the third column of each table. As usual ξ is used to denote angular velocity.

An examination of Table II will lead to several interesting conclusions. The most striking of these is that the two lines due to carbon at λ 4197.26 and 4216.14, and the line due to lanthanum at λ 4196.70, show systematically low values of the angular velocity. The following brief summary indicates more clearly their behavior in this respect, the quantities given being the differences between their values and the mean values for the list.

ϕ	0°.2	7°.7	15°.0	22°.7	29°.7	37°.7	44°.7	52°.7	59°.6	65°.7	74°.9	80°.4
4196.70	0°.0	−0°.1	−0°.2	−0°.1	−0°.1	−0°.1	−0°.2	−0°.3	−0°.4	−0°.3	−0°.7	−1°.1
4197.26	−0.1	0.0	−0.1	−0.1	0.0	−0.2	−0.2	−0.2	−0.2	−0.4	−0.5	−0.9
4216.14	−0.2	0.0	−0.1	−0.1	−0.2	−0.1	−0.2	−0.2	−0.3	−0.3	−0.5	−0.7

In the higher latitudes, of course, a small difference in linear velocity corresponds to a large difference in angular velocity, and the quantitative results are relatively much less certain than in the lower latitudes. Accordingly, while the apparent increase in the size of the differences seems to be marked in the higher latitudes, I do not feel justified at present in concluding that this is an indication that the lower parts of the reversing layer (at which these lines undoubtedly originate for the most part) show a greater retardation

TABLE II

φ	λ	Number of Plates	v km	ξ	φ	λ	Number of Plates	v km	ξ
0°.2	4196.699	21	2.076	14°.74	15°.0	4284.838	23	1.954	14°.36
	4197.257	21	2.070	14.70		4287.566	23	1.958	14.39
	4203.730	20	2.094	14.87		4288.310	23	1.943	14.28
	4209.144	21	2.105	14.95		4290.377	23	1.935	14.22
	4216.136	21	2.057	14.61		4290.542	23	1.954	14.36
	4220.509	21	2.094	14.87		4291.630	23	1.956	14.38
	4232.887	21	2.082	14.79		4294.936	23	1.947	14.32
	4257.815	21	2.092	14.85	22°.7	4196.699	12	1.791	13.78
	4258.477	21	2.080	14.77		4197.257	13	1.796	13.82
	4265.418	21	2.077	14.75		4203.730	13	1.810	13.93
	4266.081	21	2.085	14.81		4209.144	13	1.818	13.99
	4268.915	21	2.074	14.73		4216.136	13	1.791	13.78
	4276.836	21	2.081	14.78		4220.509	13	1.816	13.97
	4284.838	21	2.073	14.72		4232.887	13	1.814	13.95
	4287.566	21	2.072	14.71		4257.815	13	1.823	14.03
	4288.310	21	2.077	14.75		4258.477	13	1.806	13.90
	4290.377	21	2.062	14.65		4265.418	13	1.801	13.86
	4290.542	21	2.071	14.71		4266.081	13	1.823	14.03
	4291.630	21	2.066	14.67		4268.915	13	1.809	13.92
	4294.936	21	2.069	14.69		4276.836	13	1.803	13.88
7°.7	4196.699	14	2.016	14.44		4284.838	13	1.807	13.91
	4197.257	15	2.026	14.51		4287.566	13	1.806	13.91
	4203.730	15	2.049	14.68		4288.310	13	1.801	13.86
	4209.144	15	2.048	14.67		4290.377	13	1.796	13.83
	4216.136	15	2.028	14.53		4290.542	13	1.804	13.88
	4220.509	15	2.032	14.56		4291.630	13	1.799	13.84
	4232.887	15	2.038	14.59		4294.936	13	1.795	13.81
	4257.815	15	2.054	14.72	29°.7	4196.699	24	1.656	13.54
	4258.477	15	2.031	14.55		4197.257	24	1.668	13.64
	4265.418	15	2.028	14.53		4203.730	23	1.686	13.78
	4266.081	15	2.045	14.64		4209.144	24	1.686	13.78
	4268.915	15	2.029	14.54		4216.136	24	1.648	13.46
	4276.836	15	2.028	14.53		4220.509	24	1.685	13.78
	4284.838	15	2.022	14.48		4232.887	24	1.685	13.78
	4287.566	15	2.017	14.45		4257.815	24	1.692	13.84
	4288.310	15	2.017	14.45		4258.477	24	1.681	13.74
	4290.377	15	2.003	14.34		4265.418	24	1.673	13.68
	4290.542	15	2.007	14.45		4266.081	24	1.683	13.76
	4291.630	15	2.010	14.40		4268.915	24	1.668	13.64
	4294.936	15	2.012	14.41		4276.836	24	1.674	13.68
15°.0	4196.699	23	1.938	14.24		4284.838	24	1.673	13.68
	4197.257	23	1.952	14.35		4287.566	24	1.670	13.66
	4203.730	23	1.974	14.52		4288.310	24	1.669	13.64
	4209.144	23	1.975	14.52		4290.377	24	1.663	13.60
	4216.136	23	1.944	14.29		4290.542	24	1.670	13.66
	4220.509	23	1.979	14.56		4291.630	24	1.674	13.68
	4232.887	23	1.968	14.48		4294.936	24	1.669	13.64
	4257.815	23	1.980	14.57	37°.7	4196.699	15	1.442	12.93
	4258.477	23	1.961	14.41		4197.257	16	1.438	12.90
	4265.418	23	1.966	14.46		4203.730	16	1.462	13.11
	4266.081	23	1.964	14.44		4209.144	16	1.461	13.10
	4268.915	23	1.965	14.45		4216.136	16	1.446	12.96
	4276.836	23	1.958	14.39		4220.509	16	1.459	13.08

TABLE II—*Continued*

ϕ	λ	Number of Plates	v km	ξ	ϕ	λ	Number of Plates	v km	ξ
37°7	4232.887	10	1.401	13°10	52°7	4294.936	18	1.061	12°42
	4257.815	16	1.472	13.20	59°6	4196.699	21	0.831	11.67
	4258.477	16	1.454	13.04		4197.257	21	0.843	11.84
	4265.418	16	1.458	13.07		4203.730	23	0.858	12.05
	4266.081	16	1.465	13.14		4209.144	23	0.869	12.20
	4268.915	16	1.463	13.12		4216.136	23	0.840	11.79
	4276.836	16	1.459	13.08		4220.509	23	0.860	12.07
	4284.838	16	1.455	13.05		4232.887	23	0.865	12.14
	4287.566	16	1.454	13.04		4257.815	22	0.884	12.41
	4288.310	16	1.457	13.06		4258.477	23	0.870	12.21
	4290.377	16	1.446	12.96		4265.418	23	0.869	12.20
	4290.542	16	1.454	13.04		4266.081	23	0.879	12.34
	4291.630	16	1.452	13.02		4268.915	23	0.861	12.09
	4294.936	16	1.457	13 06		4276.836	23	0.866	12.16
44°7	4196.699	21	1.256	12.54		4284.838	23	0.858	12.05
	4197.257	21	1.263	12.62		4287.566	23	0.869	12.20
	4203.730	21	1.275	12.74		4288.310	23	0.864	12.13
	4209.144	22	1.296	12.95		4290.377	23	0.854	11.99
	4216.136	22	1.259	12.58		4290.542	23	0.852	11.96
	4220.509	22	1.287	12.86		4291.630	23	0.853	11.98
	4232.887	22	1.290	12.88		4294.936	23	0.863	12.12
	4251.815	22	1.299	12.96	65°7	4196.699	15	0.676	11.65
	4258.477	22	1.280	12.78		4197.257	16	0.671	11.56
	4265.418	21	1.285	12.84		4203.730	18	0.695	11.98
	4266.081	22	1.289	12.87		4209.144	18	0.698	12.03
	4268.915	21	1.282	12.78		4216.136	18	0.673	11.60
	4276.836	22	1.285	12.84		4220.509	18	0.692	11.93
	4284.838	22	1.280	12.78		4232.887	18	0.698	12.03
	4287.566	22	1.278	12.76		4257.815	18	0.710	12.24
	4288.310	22	1.271	12.70		4258.477	18	0.694	11.96
	4290.377	22	1.271	12.70		4265.418	18	0.696	11.99
	4290.542	22	1.274	12.72		4266.081	18	0.712	12.27
	4291.630	22	1.274	12.72		4268.915	18	0.697	12.01
	4294.936	22	1.282	12.80		4276.836	18	0.692	11.93
52°7	4196.699	16	1.030	12.06		4284.838	18	0.692	11.93
	4197.257	17	1.036	12.13		4287.566	18	0.694	11.96
	4203.730	18	1.049	12.28		4288.310	18	0.689	11.87
	4209.144	18	1.048	12.27		4290.377	18	0.690	11.89
	4216.136	18	1.036	12.13		4290.542	18	0.694	11.96
	4220.509	18	1.052	12.32		4291.630	18	0.698	12.03
	4232.887	18	1.050	12.30		4294.936	18	0.697	12.01
	4257.815	18	1.065	12.47	74°9	4196.699	37	0.409	11.16
	4258.477	18	1.055	12.35		4197.257	37	0.415	11.32
	4265.418	18	1.053	12.33		4203.730	36	0.436	11.90
	4266.081	18	1.069	12.52		4209.144	37	0.440	12.01
	4268.915	18	1.052	12.31		4216.136	37	0.416	11.35
	4276.836	18	1.054	12.34		4220.509	37	0.436	11.90
	4284.838	18	1.058	12.38		4232.887	37	0.436	11.90
	4287.566	18	1.055	12.35		4257.815	37	0.449	12.25
	4288.310	18	1.060	12.41		4258.477	37	0.435	11.87
	4290.377	18	1.052	12.31		4265.418	37	0.437	11.92
	4290.542	18	1.057	12.37		4266.081	37	0.449	12.25
	4291.630	18	1.057	12.37		4268.915	37	0.436	11.90

TABLE II—*Continued*

	λ	Number of Plates	v km	ξ	ϕ	λ	Number of Plates	v km	ξ
74°9	4276.836	37	0.439	11°98	80°4	4232.887	11	0.292	12.48
	4284.838	37	0.434	11.84		4257.815	11	0.290	12.39
	4287.566	37	0.442	12.06		4258.477	11	0.281	12.01
	4288.310	37	0.439	11.98		4265.418	11	0.287	12.26
	4290.377	37	0.443	12.09		4266.081	11	0.294	12.56
	4290.542	37	0.442	12.06		4268.915	11	0.293	12.52
	4291.630	37	0.443	12.09		4276.836	11	0.283	12.09
	4294.936	36	0.434	11.84		4284.838	11	0.291	12.43
80.4	4196.699	10	0.257	10.98		4287.566	11	0.291	12.43
	4197.257	11	0.250	11.11		4288.310	11	0.285	12.18
	4203.730	11	0.281	12.01		4290.377	11	0.280	11.96
	4209.144	11	0.271	11.58		4290.542	11	0.286	12.22
	4216.136	11	0.267	11.41		4291.630	11	0.293	12.52
	4220.509	11	0.285	12.18		4294.936	11	0.284	12.13

toward the pole than do the higher portions, although some such effect is by no means improbable. In this connection it is interesting to note that the variations in angular velocity found by Halm for the different years covered by his observations were greatest toward the pole.[1] As to the reality of the differences in the rotation rate as given by these lines, and by the mean of the entire list, there can, however, be no question, and the inference is justified that the vapors giving rise to these lines have an angular velocity of rotation which is less than the average rate of the reversing layer. In the lower latitudes the difference amounts to about 0°1 in the daily rate, which would mean a difference of about four hours in the equatorial period of rotation. For both of these elements we have independent evidence tending to show that they lie at a low level in the sun's atmosphere. In the case of carbon this is furnished by direct visual observations, while the great weakening at the limb of the lines of lanthanum and other elements of similarly high atomic weight indicates a comparatively low-lying origin for these elements as well.

Of the other lines in the list the line due to titanium at λ 4290.38 is perhaps the most interesting. This also shows a systematically low value for the angular rotation, although the difference is not so great as in the case of the carbon and lanthanum lines. It is strongly enhanced in the spark, and according to one of the more commonly

[1] *Astronomische Nachrichten*, **173**, 296, 1907.

accepted views of the enhanced lines would lie at a comparatively high level in the sun's atmosphere. It is, however, weakened at the limb, and shows a considerable shift toward the red at the limb as compared with its position at the center.[1] The weakening may perhaps be ascribed to temperature effects, but the pressure-shift and the lower rotational value are strong indications that the line originates in part, at least, at a low level.

The cases of lines giving high rotational values seem to be hardly so marked as those giving the low values which we have just discussed, although the two lines of manganese at λ 4257.82 and 4266.08 give results which are consistently large. The second of these lines is identified by Frost as present in the flash spectrum, and there is a line in his list close to the position of the first as well, although no identification is made.[2] Neither line, however, is conspicuous in intensity. At the sun's limb, beyond a slight widening, the lines seem to be little affected.

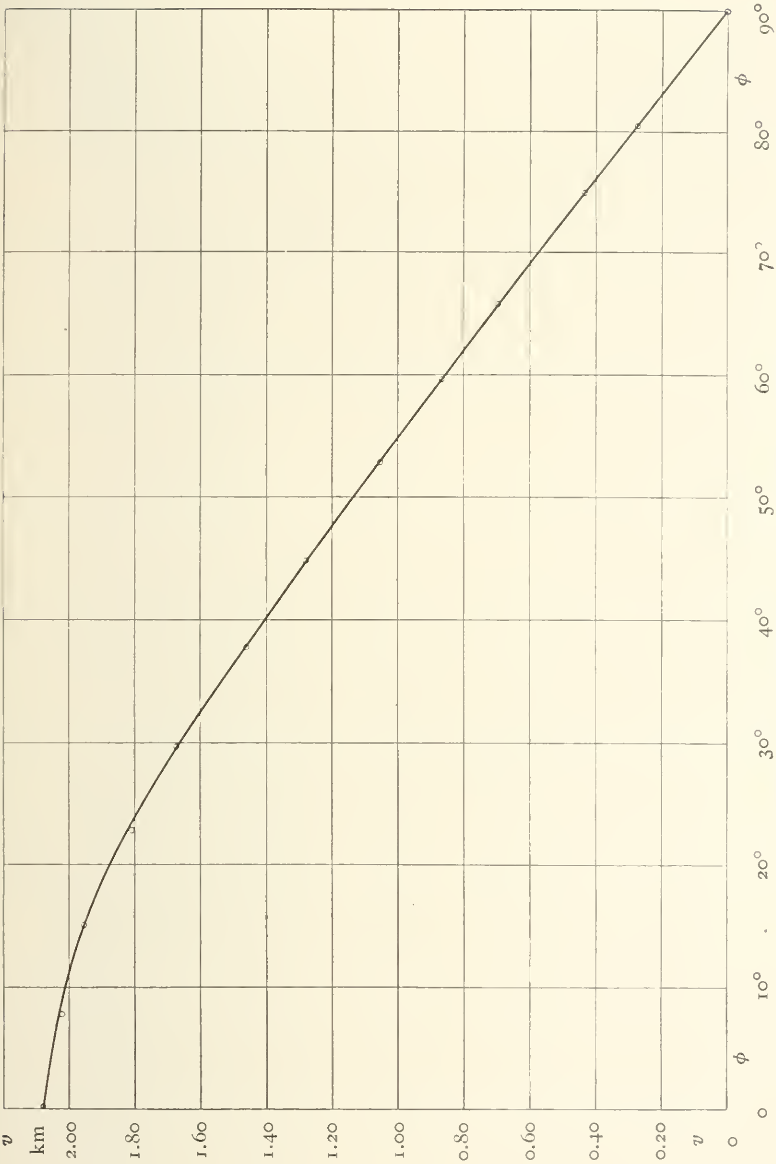
In this connection reference should be made to the work of Jewell at Johns Hopkins University in 1896. While no details of this work have ever been published, some results obtained by him are referred to in an editorial note in the *Astrophysical Journal*.[3] From his investigations Jewell concluded that the outer and inner portions of the sun's atmosphere show a difference in rotation-period amounting to several days, the lower portions having the longer period. The results found here agree with his as regards the direction of the retardation, but it would appear that the amount must be much less than that found by him. Jewell also concluded that at the lower levels the equatorial acceleration is small. So far as we may draw any inference from the result for the carbon and lanthanum lines it would seem to be decidedly opposed to this view. Jewell's conclusion that the carbon lines lie at a very low level is fully confirmed.

After this discussion of the behavior of the individual lines we may return to a consideration of the general results. Although it is clear

[1] A full discussion of this effect, first found by Halm, and later confirmed and extended by Professor Hale and myself, will be published at an early date. Our observations show that it is almost certainly due to pressure, although it may be modified by other causes as well.

[2] *Astrophysical Journal*, 22, 335, 336, 1900.

[3] *Ibid.*, 4, 138, 1896.



Curve Showing Radial Velocity at Different Latitudes

that different lines may give different values for the rate of rotation, it would seem that in order to obtain an average value for the rotational velocity of the reversing layer we can hardly do better than to take a general mean for all the lines. If we form mean values from the quantities given in Table I we are led to the following summary. In the formation of the means such plates as have been measured twice have been assigned double weight.

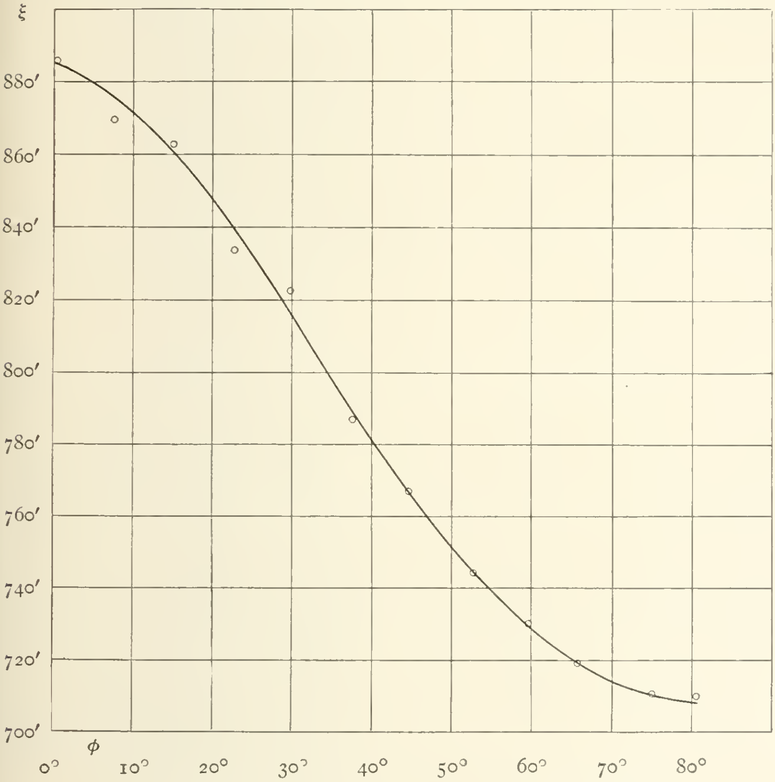
ϕ	Weight	v km	ξ	Period Days
0°2	21	2.078	14°75	24.39
7.7	15	2.023	14.50	24.83
15.0	23	1.957	14.39	25.01
22.7	13	1.808	13.92	25.86
29.7	24	1.673	13.68	26.32
37.7	15	1.461	13.11	27.46
44.7	23	1.279	12.77	28.19
52.7	18	1.055	12.35	29.15
59.6	24	0.864	12.13	29.68
65.7	20	0.696	11.99	30.02
74.9	33	0.434	11.85	30.38
80.4	11	0.277	11.84	30.40

The two curves which accompany this paper give a graphical representation of the quantities in the table above. In the first and larger curve the radial velocities are plotted as ordinates with the latitudes for abscissae. The second curve represents the change of the angular velocity ξ with the latitude. Both of these curves have been drawn with due regard to the weights of the normal points, which accounts for the apparently abnormal deviation from the curves of the points of lower weight. This is especially true for the two points at 7°7 and 22°7, which are based on comparatively few observations, and which show by far the largest deviations from both curves.

One of the most interesting features of these results is the form of the angular velocity-curve. Starting with a curvature strongly convex upward, its slope rapidly becomes very steep. At about 30° or 35° of latitude there is a point of inflection, and in the higher latitudes it approaches the asymptotic form. In other words, the rate of change of the angular velocity of rotation with the latitude increases from the equator to about latitude 30°, at which point it is greatest. It then begins to decrease, and in the highest latitudes becomes very small. An extrapolation from the curve gives for the daily angular rotation

rate at the pole a value of 11°.7, which would correspond to a period of rotation of 30.6 days.

In order to facilitate the comparison of these results with those of Dunér and Halm, a short table is appended giving their values for the latitudes which we have employed here. Their results are taken from



Curve of Change of Angular Velocity, ξ, with Latitude, φ

the papers already referred to.[1] Since Dunér's values are confined to the six latitudes from 0° to 75°, differing by intervals of 15°, his results are given for these latitudes alone. The much greater number of latitudes employed by Halm, however, makes it comparatively

[1] In his paper Halm has derived mean values from his series of observations for 1901 to 1906, although he ascribes the large systematic differences of the results for different years to actual variations in the period of rotation. His mean values are employed here.

simple to construct a curve and take from it with sufficient accuracy the values corresponding to the latitudes required. The quantities given in the table have been obtained in this way, and have, of course, a considerable advantage over those given by Dunér and myself, since they have had the benefit of the smoothing-out effect of the curve.

	Linear Velocity			Angular Velocity		
ϕ	Dunér km	Halm km	Adams km	Dunér	Halm	Adams
0°2	2.08	2.05	2.08	14°8	14°6	14°7
7.7		2.02	2.02		14.5	14.5
15.0	1.97	1.95	1.96	14.5	14.3	14.4
22.7		1.83	1.81		14.1	13.9
29.7	1.70	1.68	1.67	13.9	13.7	13.7
37.7		1.49	1.46		13.4	13.1
44.7	1.28	1.32	1.28	12.8	13.2	12.8
52.7		1.10	1.05		12.9	12.4
59.6	0.82	0.90	0.86	11.5	12.6	12.2
65.7		0.72	0.69		12.4	12.0
74.9	0.39	0.45	0.43	10.7	12.3	11.8
80.4		0.29	0.28		12.4	11.8

An inspection of these results shows that in the lower latitudes all three series of observations give values which are fairly accordant. Above 30° of latitude, however, Halm's results become larger than those in the other two series, and this continues to be true in the higher latitudes. At about 45° or 50° Dunér's values cross my own, and fall considerably below in the higher latitudes. The general conclusion accordingly, is that the photographic results give a curve of angular velocities which in the higher latitudes is intermediate between those of Dunér and Halm. This curve agrees with that of Halm in showing a falling-off in the rate of the variation in higher latitudes, but the effect seems to begin at a lower latitude than is indicated by Halm's results.

As regards the interesting question of a long period variation in the rotation rate the results given here are, of course, not decisive, since the interval covered by them amounts to rather less than fourteen months. For this interval there seems to be no variation of appreciable size. The fact, moreover, that the values found agree as well as they do with the mean values of Halm for his entire series of observations would seem to furnish some presumption against the existence of such a variation, at least of such magnitude as was found by him.

At present the question must be regarded as one for future observations to decide.

Since the permanency of form of the velocity-curve is thus open to possible doubt, it has not seemed desirable to devote any large amount of attention at present to the consideration of empirical equations which might satisfy it. A preliminary solution by least squares of an equation of the form given by Faye,

$$v=(a-b\sin^2\phi)\cos\phi,$$

showed that the curve could be reasonably well satisfied by an equation of this type, the largest residual amounting to about 0.024 km. The residuals (computed − observed values) were, however, consistently positive in mean latitudes, and consistently negative in high latitudes. This naturally suggested the addition of a term in $\cos\phi$, giving an equation of the form

$$v=(a-b\sin^2\phi+c\cos\phi)\cos\phi\ ,$$

or, in another form,

$$v=(a'+b'\cos\phi+c'\cos^2\phi)\cos\phi\ .$$

A solution by least squares of this equation for the twelve latitudes gave the following residuals:

ϕ	C.−O. km
0°2	−0.008
7.7	+0.016
15.0	0.000
22.7	+0.013
29.7	−0.007
37.7	+0.004
44.7	−0.004
52.7	0.000
59.6	0.000
65.7	−0.001
74.9	+0.002
80.4	+0.004

The only large residuals are those given by the points of low weight at 7°7 and 22°7, and these are by no means excessive. Though an equation involving three constants is, of course, inferior to one containing but two, the very satisfactory size of the residuals given by it, and the simplicity of its form probably justify its use.

In concluding this discussion it will be useful for purposes of comparison with the results obtained from the measures of spot, faculae,

and flocculi positions, to add a short table giving the values of the daily angular rotation for every 10° of latitude. These have been taken from the curve and are as follows.

ϕ	ξ	Period Days
0°0	14°72	24.46
10.0	14.52	24.79
20.0	14.13	25.48
30.0	13.62	26.43
40.0	13.03	27.63
50.0	12.53	28.73
60.0	12.15	29.63
70.0	11.90	30.25
80.0	11.78	30.56

A comparison of the probable errors of these results with the probable errors of the visual determinations of Dunér and Halm is somewhat difficult on account of the difference in the character of the measurements. In the work of both Dunér and Halm a considerable number of settings of the micrometer wire were made upon each of two lines (by Dunér twelve to twenty-four, by Halm eight), and these series of settings, combined for the two lines, furnish separate observations of the velocity. In the present photographic investigation a smaller number of settings was made upon each of a considerable number of lines, and the values given by all the lines measured on a plate are combined to form a single determination. For general purposes, however, it will be sufficient to compare the probable error in the determination from a single line on the photographic plate, with the probable error from a series of visual observations equal in number to that of the lines on the plate. This evidently gives a decided advantage to the visual results in the comparison, since the mean of two lines is used for them as well as a greater number of settings on each line. On the other hand it is clear that in the photographic results such lines as give systematically large or small values throughout the whole series of observations should be omitted in the formation of the probable error. We have discussed six cases of this sort in connection with Table II, namely, the lines λ 4196, 4197, 4216, 4257, 4266, and 4290.38. If we omit these we have left a total of fourteen lines to each plate. A determination made from several

plates taken at random from the series gives as the probable error for a single line,

$$\epsilon = \pm 0.015 \text{ km};$$

or, for the mean value from the plate,

$$\epsilon_0 = \pm 0.004 \text{ km}.$$

To compare with these we have a series of determinations by Halm in 1903[1] averaging fifteen observations for each latitude. He gives for these

$$\epsilon = \pm 0.070 \text{ km}$$

as the probable error of a single observation, and

$$\epsilon_0 = \pm 0.018 \text{ km}$$

as the probable error of the group. Dunér has not given the probable errors for his completed series of observations. For his earlier results they amount to about double those given by Halm.

We are certainly justified in concluding from this comparison that for the same number of measurements the photographic method is capable of furnishing results of higher precision than the visual, at least in so far as inferences of this kind can be drawn from comparisons of probable errors. As in most cases of quantitative spectroscopic work, however, it is probable that in both the visual and the photographic series of observations the effects of small systematic errors begin to be felt before the limits of accuracy defined by the probable errors of groups of results are reached. As regards this class of error it is difficult to conclude with which method of observation the advantage lies. Since the observer is free during the exposure of the photographic plate to do any small amount of guiding necessary to hold the image of the sun in a definite position, the error arising from wandering of the image should be less than in visual measures by a single observer. On the other hand any error which does enter from this source affects all of the lines upon the photographic plate, while in the visual measures it affects each set of pointings only. Perhaps the most valuable general conclusion that can be drawn from the discussion is that the degree of accuracy of measurement attainable on the photographs is so high that it warrants the use of the greatest precautions to avoid small systematic errors.

[1] *Transactions of the Royal Society of Edinburgh*, 41, Part 1, 96.

The investigations will be continued with the use of the more powerful apparatus of the tower telescope, and it is hoped that a substantial gain in accuracy may be attained. Among the superior advantages for such work possessed by this instrument we may mention the following: greater linear scale of the plates; a higher degree of accuracy of setting for the various position angles on the sun's image, as well as the possibility of reaching all latitudes on the sun's surface at all times of the year; less liability to changes of temperature on the part of the grating during the exposures; and finally some improvement in the definition of the solar image, and greater freedom from astigmatism and change of focus while the photographs are being obtained.

The more important conclusions derived from this investigation may be summarized as follows:

1. In lower latitudes the values obtained for the rotational velocity agree closely with those of Dunér and Halm. In higher latitudes they are intermediate between the results of these two observers.

2. The rate of change of the rotational velocity with the latitude is greatest at about 30° of latitude. It becomes less in higher latitudes, and beyond 70° is very slight.

3. Different lines give slightly different rates of rotation. Lines of carbon and lanthanum, elements which lie at a low level in the sun's atmosphere, give values for the daily rate about 0°1 less than the mean values for all the lines. An enhanced line of titanium also gives a slightly lower rate of rotation, while two lines of manganese included in the list give systematically high results.

4. There is no appreciable variation in the rate of rotation during the fourteen months covered by the observations.

5. A comparison of probable errors indicates a substantial gain in accuracy for the photographic results as compared with the visual, so far as accidental errors of measurement are concerned.

I am indebted to Professor Hale for an active interest in this research, and many valuable suggestions during its progress; also to Miss Lasby of the Computing Division for her most efficient performance of the exacting work involved in the measurement and reduction of the large number of plates.

Mount Wilson, Cal.
September 1907

THE SELECTIVE REFLECTION OF SALTS OF CARBONIC AND OTHER OXYGEN ACIDS[1]

By LEIGHTON B. MORSE

I. THE SELECTIVE REFLECTION OF CARBONATES AS A FUNCTION OF THE ATOMIC WEIGHT OF THE BASE

If there were a regular displacement of the resonance periods of simple molecules in salts having the same acid radical, it should first be sought in compounds of simple bases having the same valence. The carbonates seemed especially well adapted to such a study since a large number could be obtained in a suitable form as minerals. The absence of water of crystallization adds further to the simplicity of the molecular structure of the carbonates of the eight elements (*Mg, Ca, Mn, Fe, Zn, Sr, Ba,* and *Pb*) examined, for which RCO_3 may be written as a general formula, *R* being a bivalent metal.

Partial data were obtainable on the reflection of the carbonates of two elements, calcium and magnesium. E. Aschkinass,[2] in a study of anomalous dispersion, had recorded the reflection of calcite and marble. He found maxima in the reflection of calcite at 6.67 μ and 11.40 μ, and of marble at 6.69 μ and 11.41 μ. By the method of "Reststrahlen" as discovered by H. Rubens and E. F. Nichols,[3] J. T. Porter[4] found a maximum in the reflection of white marble at 6.77 μ.

Some time later W. W. Coblentz[5] gave the reflection of calcite from 4 μ to 11 μ, and of magnesite from 4 μ to 12.4 μ, missing a second band in magnesite and not continuing to the second band in calcite, or to the region of the third bands in either. In the work of Aschkinass, Coblentz, and the present writer the wave-length determinations were referred to the dispersion of a rock-salt prism.

[1] *Phoenix Physical Laboratory Contributions, No. 11.*

[2] *Annalen der Physik,* 1, 60, 1900.

[3] *Ibid.,* 60, 418, 428, 1897.

[4] *Astrophysical Journal,* 22, 229, 1905.

[5] *Investigations of Infra-red Spectra,* Parts III and IV, 81, 1906.

ARRANGEMENT OF APPARATUS AND ADJUSTMENTS

When the shutter at K was raised the image of a Nernst glower at N (Fig. 1)[1] was focused by the silvered concave mirror M_1 upon the surface under examination at S. A second silvered concave mirror M_2 caught the reflected beam and formed a secondary image of the source on the collimator slit C. These mirrors, M_1 and M_2, were adjusted near each other in order to make the angle of incidence on the surface at S as small as possible.

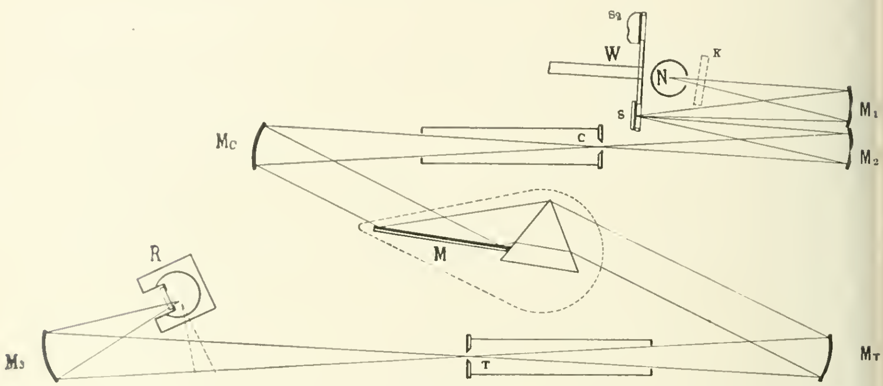


FIG. 1

After resolution by the spectrometer, the section of the spectrum passing through the rear slit T was focused on one of the radiometer vanes by a similar silvered concave mirror M_3. The mirrors M_1 and M_2 were adjustable about horizontal and vertical axes perpendicular to the axes of the mirrors. A base provided with leveling screws aided in the adjustment of the mirror M_3.

A small angle of incidence on the surface whose reflection was to be measured, 5° to 6°, was one of the advantages of this arrangement. Also the ability to use plane surfaces of small dimensions, but a little larger than the Nernst glower, made it less difficult to obtain suitable specimens.

Source.—A Nernst glower, operated on alternating current from the city lighting circuit was first used, but irregular fluctuations of

[1] The writer wishes to thank Mr. C. C. Chapin of the department, for valuable assistance given in preparing the curves and for drawing the figure.

the voltage produced not only sudden changes in the intensity of the radiation, but the expansion and contraction of the end wires continually shifted the image of the glower on the slit. Later a direct current glower (0.8 ampere, 110 volts) was used in a 120-volt storage-battery circuit, and slow variations in the current could be compensated for by a variable resistance, with the aid of an ammeter in circuit, reading to hundredths of an ampere.

After making these changes and improving the asbestos chimney used to protect the glower from variable air currents, conditions were so constant that no difficulty was experienced in holding the image of the glower on the spectrometer slit, C, for hours with no apparent shift in its position, and the emission of the glower remained equally constant. But for its selective emission, the Nernst glower used in this way would have been an ideal source.

Mounting of the specimens.—Three of the plane-polished mineral surfaces for which the reflection was to be measured, and a polished plane silver mirror were mounted over the four holes 2 cm in diameter in a wheel W (Fig. 1). The back face of the disk against which the surfaces were laid was ground as plane as possible on plate glass. But the final adjustment of the surfaces, to bring them successively into the same position when the wheel was rotated from one position to the next, was made by observing the reflected image of an incandescent-lamp filament in the field of a telescope with cross hairs. The smaller surfaces were mounted in cork and then adjusted on the wheel.

Spectrometer.—A Schmidt and Haensch reflection spectrometer with mirrors of 4 cm aperture and 35 cm focal length was used. By the aid of the Wadsworth[1] mirror-prism arrangement, the spectrometer arms remained fixed; and adjustment for the minimum deviation of one wave-length held for all. The face of the rock-salt prism was 5 cm by 8 cm and its refracting angle 59° 59′ 15″. A rotation of the spectrometer arm by 4′ 50″ moved the center of the slit 1 mm. As the front and rear slits were always of equal width, the purity of the spectrum at any setting was as great as the energy necessary for a sufficient radiometer deflection would allow.

Wave-lengths were calculated from the indices of refraction for

[1] F. L. O. Wadsworth, *Phil. Mag.*, 38, 337, 1894.

rock salt given by H. Rubens[1] to 8.67 μ and the corrected values of H. Rubens and A. Trowbridge[2] were used for longer waves. Rotating the prism-table carrying the Wadsworth mirror-prism arrangement 1′, corresponded to a change in wave-length from 6.50 μ to 6.60 μ, from 11.60 μ to 11.65 μ, or from 14.20 μ to 14.24 μ, respectively.

As the spectrometer was arranged with its arms parallel and close to the prism-table, it was impossible to use any circular hood to protect the salt prism from moisture when it was not in use. In order that greater care might be taken to avoid touching the prism-table when removing and replacing the box used for this purpose, its top was made of glass. The plane sides and semi-cylindrical end of copper, outlined by dotted line in Fig. 1, left a space of 1 cm between the box and the pointed glass prism-table. A brass plate was mounted below the prism-table on a heavy collar about the spectrometer axis. The lower edge of the box fitted into a trough about the outer edge of this plate. Glycerine was used in the trough as a seal and P_2O_5 served as a drying agent.

Radiometer.—Behind the mirror M_3 was an inner brick wall to which the heavy shelf supporting the radiometer R and mirror M_3 (Fig. 1) was fastened. The radiometer was inclosed by a blackened compoboard box, not shown in the diagram. The Nichols' radiometer used was so similar to those described by other observers that only a few details of its construction are necessary. The mica vanes, 0.75 mm by 5 mm, were mounted about 5 mm apart and their front surfaces blackened with platinum black, held by shellac. The window of rock salt was protected by a P_2O_5 dryer when the radiometer was not in use. The half-period of the suspended system varied from twenty-five to fifty-five seconds, depending upon the air pressure in the radiometer. Often the general form of a reflection curve was obtained on one day and observations requiring the most sensitive conditions were made the following day, when the leak had increased the pressure, and with it the period and sensibility of the radiometer. The leak was so small that sufficiently accurate measurements have been made on the third day after the radiometer was pumped out, but the longer

[1] *Annalen der Physik*, 54, 482, 1895.

[2] *Ibid.*, 60, 733, 1897.

period made observing tedious. Generally the pressure used was such that the radiometer was slightly ballistic.

Because of the symmetry in the construction of the radiometer suspension, tremors of the building due to the heavy traffic outside at no time interfered with the progress of the work. Throughout the work no trouble arising from static charges on the radiometer vanes was encountered, not even when the stop-cock connecting the radiometer with the mercury pump was left open, a condition mentioned by Coblentz[1] as especially favorable for static disturbances. This was doubtless due to the presence of a small amount of radioactive material placed in the bottom of the radiometer case.

The image of an incandescent-lamp filament, projected on a scale one meter distant by a light concave mirror[2] attached to the lower end of the radiometer suspension, served to indicate deflections. An asbestos box covered the lamp used as an index and permitted light to pass from it only through a narrow slit on the side toward the radiometer. Diaphragms were used in addition to protect the radiometer from the heat of the lamp.

The walls of the room, an inner grating room, were light-tight with the exception of protected openings for ventilation. Unslaked lime was always kept in trays about the room to reduce the moisture in the air.

METHOD OF OBSERVING

A zero reading was taken before and after each deflection. Conditions were held so constant that the mean of two observations on the silver surface, one made before, and the other after observations on the three mineral surfaces, was sufficiently accurate for most of the work. There have been differences in these two deflections from silver which would have caused errors greater than those in reading the deflections from the mineral surfaces. Such occurrences were rare, even at points in the spectrum where the reflection from the mineral surfaces was high, and such observations were invariably repeated. But when the greatest accuracy in determining the posi-

[1] *Investigations of Infra-red Spectra*, Part I, Appendix III.

[2] To Dr. S. R. Williams the writer is much indebted for plating the mirror with platinum. The reflecting surface obtained remained in good condition throughout the work.

tion of a maximum was required, comparison was made between the mineral and silver surfaces at equi-distant points over the crown of the curve. These observations were then repeated with new settings on the same series of points in the spectrum and the maximum was determined from the average results.

When preliminary observations indicated little difference in the reflection maxima of two substances, as for example calcite and aragonite, both $CaCO_3$, or siderite, and rhodochrosite ($Fe = 55.5$, $Mn = 54.6$), they were mounted in the wheel together with the silver mirror. This made it possible to determine the reflection of the two under almost identical conditions and slight errors in reading the spectrometer vernier were eliminated from the comparison. When the position found for a maximum seemed irregular, as for example the band of smithsonite in the third region, in addition to the usual frequent checking of the calibration curve of the spectrometer by setting on the sodium line, further assurance was sought by repeating observations with the substances in question and calcite in the "wheel" together.

DESCRIPTION AND ANALYSES OF SPECIMENS

Three of the mineral reflecting surfaces were polished by Schmidt and Haensch, witherite, strontianite, and aragonite. The others were polished in the laboratory. The polish required for such long waves was much less than for ordinary optical measurements. In fact the magnesite specimens containing silica were used when at normal incidence the image of an incandescent lamp one meter distant was barely visible in a reading-telescope. The range of quality of surfaces was from brilliant to very dull in the order given: witherite, strontianite, smithsonite, aragonite, calcite, rhodochrosite, siderite, cerussite, magnesite.

The writer is much indebted to Dean William Hallock for a number of useful suggestions concerning the preparation of the specimens and also for his friendly interest shown in many other ways.

To Professors Moses and Luquer and to Mr. Lamme, of the Department of Mineralogy, he is variously indebted for kindly advice in mineralogical matters and for the generous loan of materials from the departmental collection.

He is further indebted to Professor L. P. Gratacap, of the Museum

of Natural History, for the following description of the specimens used. The analyses were made by Dr. H. T. Beans, of the university.

1. Magnesite, No. 2, $MgCO_3$, from Oberdorf, Styria. Section from a mass, subcrystalline, fibrous, white; slight schillerization on surface from crystalline texture. Contained magnesium calculated as MgO, 15.94%; calcium calculated as CaO, 31.73%; Silica, 1.03%; water liberated at bright red heat, 0.48%.

2. Calcite, $CaCO_3$. Polished rhombohedral cleavage surface. Perfect texture, transparent.

3. Aragonite, $CaCO_3$. Section of transparent crystal. Surface used was a polished prism face.

4. Rhodochrosite, $MnCO_3$, from John Reed Minc, Lake Co., Col. Pale pink, semi-transparent, surface nearly parallel to face of rhombohedron.

5. Siderite, $FeCO_3$. Light brown, crystalline, lamellar. Contained iron calculated as FeO, 44.54%. Qualitative tests show some ferric iron and large quantities of manganese. No other qualitative tests were made.

6. Smithsonite, No. 1, $ZnCO_3$. Crystalline, dense texture, marked by lines of spheroidal intergrowth, pale yellow, to mottled in color, transparent, darkened by iron oxide nodule. Contained zinc calculated as ZnO, 60.58%; water liberated at bright red heat, 0.67%. The sample contains considerable iron.

7. Smithsonite, No. 2, $ZnCO_3$, from Laurium, Greece. Compact, fibrous, crystalline, pale milky gray in color, sub-transparent; original surface slightly mammilated. Contained zinc calculated at ZnO, 61.83%; water liberated at bright red heat, 0.59%.

8. Strontianite, $SrCO_3$. Massive, sub-fibrous, distinctly crystalline in structure, pale asparagus green.

9. Witherite, $BaCO_3$. Massive, fibrous, columnar in structure, pearl gray.

10. Cerussite, $PbCO_3$, from Monte Poni, Sardinia. Section obtained from twinned crystal, white, transparent.

RESULTS

Three bands of marked reflection[1] were found in all of the specimens examined (Figs. 2–7), but in no case were there more than three bands found in the spectrum between 4 μ and 15 μ. The bands fall into three distinct regions in the spectrum grouped about 6.7 μ, 11.5 μ, and 14.5 μ. To this grouping only one exception was found, magnesite, No. 1; and from the shape of its reflective curve the presence of a silicate was suspected. This was verified by a chemical analysis, which showed 8.95 per cent. of silica, calculated

[1] The reflection percentages given in the curves are based upon silver assumed total. The actual reflection of silver given by E. Hagen and H. Rubens (*Annalen der Physik*, 11, 73, 1903) increases from about 98 per cent. at 4μ to 99 per cent. at 14μ.

as SiO_2, together with 4.56 per cent. of water liberated at bright-red heat. Because of these impurities this specimen will not be considered further.

These regions where the carbonate reflection bands occur are distinct from the regions where the salts of other acids as far as known show reflection maxima. This verifies and gives a broader foundation for the conclusion reached by A. H. Pfund[1] based on a study of single bands in several nitrates and sulphates: "That the mechanism giving rise to these maxima was localized within the acid radical."

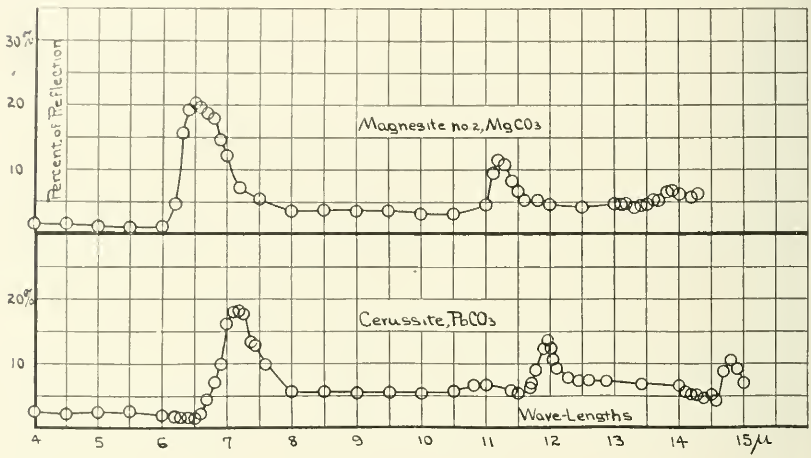


FIG. 2

In general the larger the atomic weight of the base the greater was the wave-length where the maximum reflection occurred, as will be seen by an examination of Figs. 2–7, of which Fig. 8 presents a condensed summary.

The following exceptions appear in the reflection curves found: siderite ($FeCO_3$) in the first region, either smithsonite ($ZnCO_3$) or siderite ($FeCO_3$) and rhodochrosite ($MnCO_3$) in the second region, and all three in the third region. Also, the reflection maxima of calcite and aragonite, both $CaCO_3$, differ considerably in the second region both in magnitude and position; and the aragonite maximum may lie a little toward the long waves from calcite in the first region.

[1] *Astrophysical Journal*, 24, 23, 1906.

In attempting to answer the question: Can a law be found for the general shifting of the bands toward the long waves with the increase

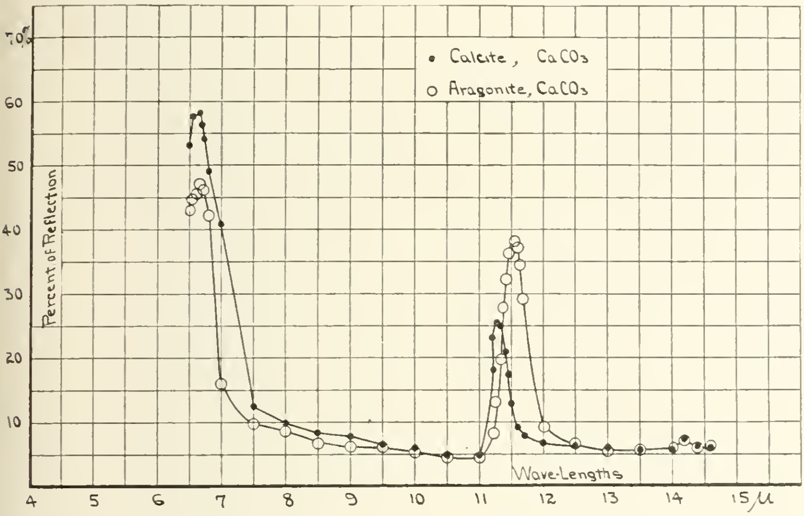


FIG. 3

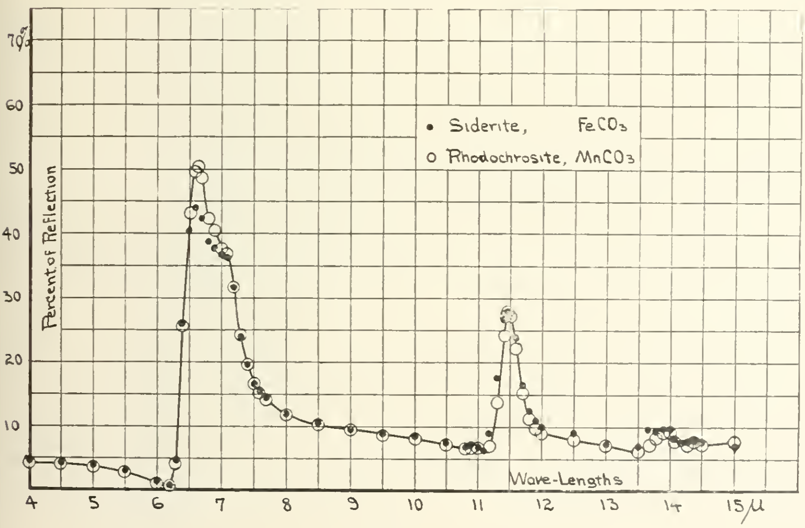
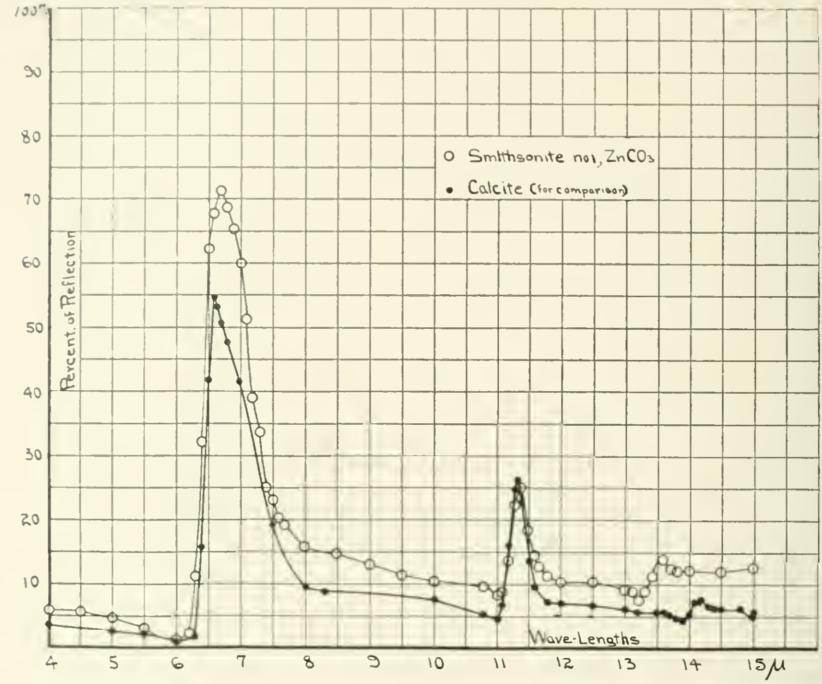


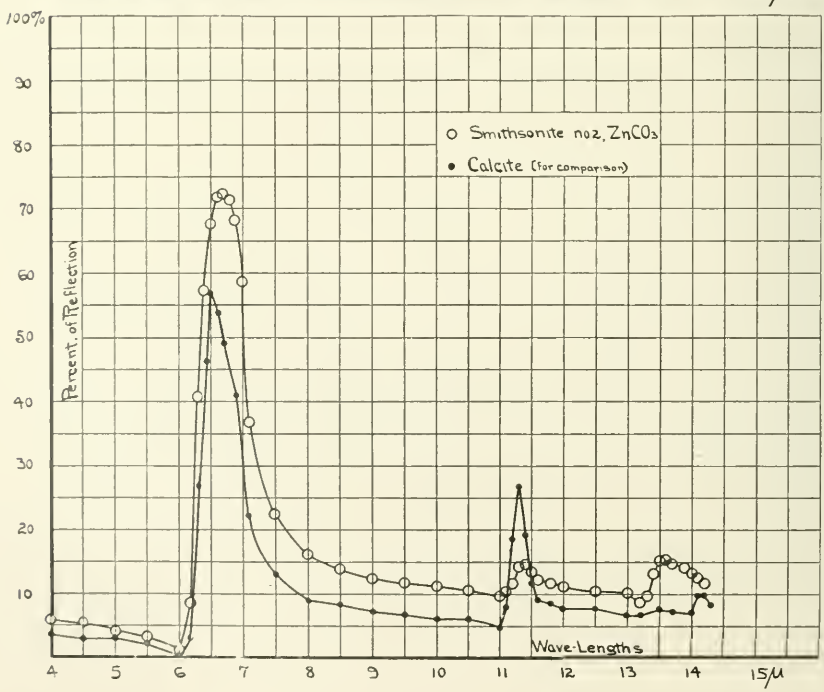
FIG. 4

in atomic weight of the base ? a straight line was drawn in each region through the cerussite ($PbCO_3$) and calcite ($CaCO_3$) maxima. These



100%
90
80
70
60
50
40
30
20
10
Percent. of Reflection
○ Smithsonite no1, ZnCO3
● Calcite (for comparison)
Wave-Lengths
4
5
6
7
8
9
10
11
12
13
14
15μ

FIG.



100%
90
80
70
60
50
40
30
20
10
Percent. of Reflection
○ Smithsonite no2, ZnCO3
● Calcite (for comparison)
Wave-Lengths
4
5
6
7
8
9
10
11
12
13
14
15μ

FIG.

points were selected to determine the lines *C*1, *C*2, *C*3, Fig. 8, because of the large difference in the atomic weight of the bases. Calcite rather than magnesite was selected as the lower point in determining the line because its structure gave evidence of its being the purer specimen.

Straight lines fitted the results better than any simple curve, showing that in general the shifts in position of the maxima are directly

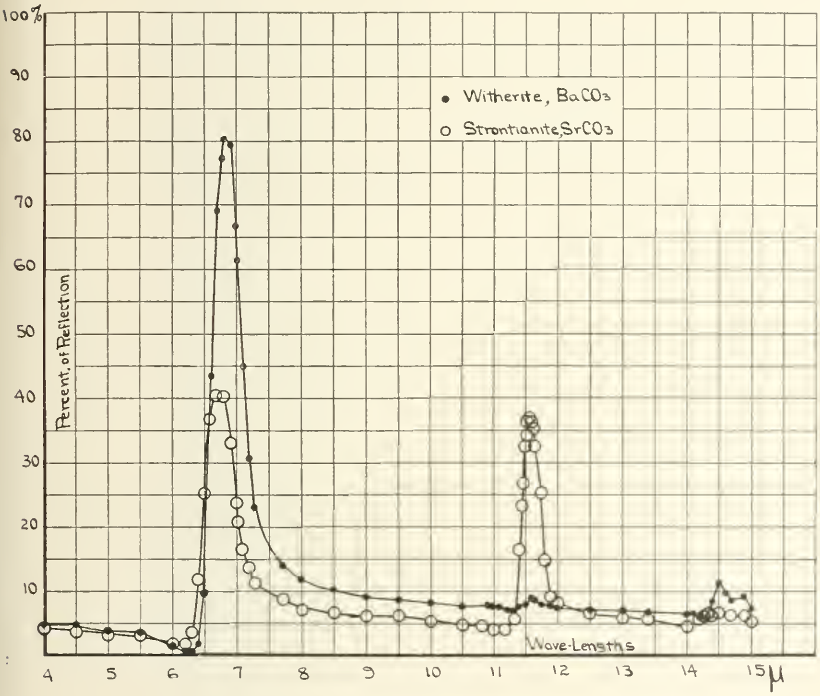


FIG. 7

proportional to the change in the atomic weight of the base. The smithsonite ($ZnCO_3$) band in the third region shows the greatest deviation.

A second specimen of smithsonite gave a band shaped differently, especially in the second region, but having practically the same maxima as the first in all three regions. Its band in the third region was several times as broad as the calcite band and had its maximum on the side toward the short waves. With the exception of the magnesite,

the other points showing the greatest deviation from the straight lines have been mentioned in the third preceding paragraph. These lines drawn through the cerussite and calcite (*Pb* and *Ca*) maxima, to aid in comparing the results, are practically parallel. All but three of the eighteen points in the first two regions lie near these parallel lines, which indicates that the average displacement in each region due to the same change in atomic weight of the base is of the same order of magnitude.

Half of the points in the third region are considerably off the line, but, as will be shown later, a larger allowance for errors must be made in this part of the spectrum. The reflection curves usually published where a rock-salt prism is used end before the beginning of these bands because of the rapid increase, with wave-length, in the absorption of rock salt in this part of the spectrum.

In the comparison of maxima it is well to recall that a band's position may be influenced by impurities in the specimen, by the selective emission of the source, or by the selective absorption of any medium in the path of the beam. A small per cent. of a salt with a strong reflection band near the true band of the carbonate might easily serve to broaden the band and shift its maximum, especially when the true band is of low intensity.

Errors.—In some respects the position of two of the three regions is rather unfortunate. In the first region the intensity of the emission of a Nernst glower varies[1] both rapidly and irregularly with change in wave-length, and water vapor has an absorption[2] band with a maximum at 6.1 μ. In the third region the rapidly increasing absorption of the rock salt used as a prism and radiometer window would tend to displace the apparent position of maxima toward the short wave-lengths by an amount depending upon the form of the band. With slits 1 mm in width the reflection from silver at 14 μ was 119 divisions and but 47 divisions at 15 μ. Some of the bands in this region were so low that it was possible to detect them only by repeating observations at short wave-length intervals, and when found it was difficult to determine the precise position of the maximum. The uncertainties besetting measurements here are further

[1] W. J. H. Moll, *Onderzoek van Ultra-roode Spectra*, Plate VIII, Utrecht, 1907.

[2] The total path of the beam in air was 2.7 meters.

increased by the wide slits[1] employed. The dispersion theory calls for a sudden drop just preceding a rise in reflection and, in nearly all cases, the curves show this in the third, as well as the two earlier bands.

Complexity of bands.—Irregularities in the shape of nearly all the bands in the first region, which were prominent when the points observed could all be plotted on a larger scale, are still quite distinct in the curves shown, especially in siderite and rhodochrosite. These irregularities, together with Coblentz's observation of two maxima in the first bands of calcite and magnesite suggest that a higher resolving power would show all the carbonate bands in the first region to be complex.

Few irregularities in the shape of bands were observed in the second region, but several appear in the third, though here the deflections were so small that it was difficult to distinguish between small errors in observation and true irregularities in the curve. The impurity of the spectrum resulting from the wide slits necessary in the study of the second and third bands may have not only depressed the maxima but concealed the details of any characteristic structure within the bands.

Structure, etc.—In general the data on record do not indicate that differences in the position of bands in substances with the same chemical composition should be expected so far out in the infra-red. But, if both aragonite and calcite, both calcium carbonate, are reasonably pure, as their structure would indicate, such a difference exists in the reflection from their crystals. The second bands differ considerably both in their position and in their magnitude. Moreover, the higher reflection of aragonite in the second region cannot be attributed to a surface difference, as calcite shows the higher reflection in the first.

No classification of the results according to the chemical group to which the base belongs has been possible. If displacements due to this are present they must either be irregular or secondary in magnitude to those produced by a change in the atomic weight. Neither has any simple relation been found to exist between the wave-lengths

[1] In the first, second, and third regions, slits 0.3 mm, 0.8 mm, and 0.1 mm in width were generally used.

of the regions within which the bands fall. For convenience of comparison the wave-lengths of the reflection maxima are given in Table I.

TABLE I

Substance	Chemical Composition	Atomic Weight of Base	Reflection Maxima		
			Band 1	Band 2	Band 3
Magnesite	$MgCO_3$	24.2	6.5 μ	11.2 μ	13.9 μ
Calcite	$CaCO_3$	39.7	6.6	11.31	14.2
Aragonite	$CaCO_3$	39.7	6.65	11.55	14.2
Rhodochrosite	$MnCO_3$	54.6	6.63	11.47+	14.0−
Siderite	$FeCO_3$	55.5	6.60	11.47−	13.9−
Smithsonite	$ZnCO_3$	64.9	6.7	11.38	13.6
Strontianite	$SrCO_3$	86.9	6.76	11.56	14.37
Witherite	$BaCO_3$	136.4	6.86	11.60	14.5
Cerussite	$PbCO_3$	205.4	7.2	11.94	14.8

EARLIER DATA IN AGREEMENT

The earlier data on the reflection of the anhydrous salts of carbonic and other simple acids, though meager, are still in agreement with the conclusions drawn from carbonates concerning the shift of bands with change in the atomic weight of the base.

Carbonate.—In the data of Coblentz on calcite and magnesite the wave-lengths of both components of the complex band in the two substances lie in the order of the atomic weights of the bases. Although Coblentz gives the reflection of magnesite to 12.4 μ, his observations were at such long wave-length intervals that he missed the second reflection band which was doubtless present because the specimen used, judging from the height of the first band, was superior to the one here described.

Nitrate.—Pfund found that KNO_3 ($K=38.9$) and $AgNO_3$ ($Ag=107.1$) had bands at 7.05 μ and 7.45 μ respectively, shown by crosses in Fig. 8. Coblentz's value for KNO_3, 7.15 μ, is shown by a circle.

TABLE II

Substance	Chemical Formula	Atomic Weight of Base	Maxima for First Band		
Anhydrite	$CaSO_4$	39.7	....	8.6 μ	9.1 μ
Celestite	$SrSO_4$	86.9	8.2 μ	8.76	9.1
Barite	$BaSO_4$	136.4	8.35	8.9	9.1

Sulphate.—The maxima in the reflection of simple anhydrous sulphates are given in Table II, compiled from the data of Coblentz.

In each case the maximum in the middle column is the highest and corresponds more closely to the center of the complex band. These values are plotted with the atomic weight of the base in Figure 8,

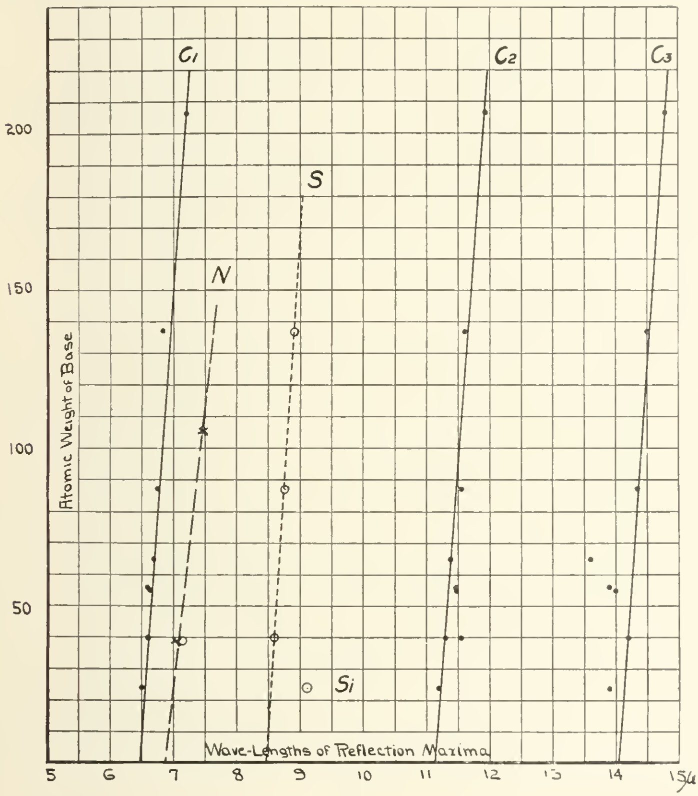


FIG. 8

and the line S drawn connecting these points is practically straight, showing that the displacements are proportional to the change in the atomic weight of the base, which agrees with the statement made regarding the displacement in carbonates. The line N, through the nitrate points, and the line S, through the sulphate points, are both approximately parallel to the lines, C_1, C_2, and C_3, drawn for the three carbonate bands. From this we are led to suspect that the rate of

shift of the band with increase in the atomic weight of the base is of the same order of magnitude in carbonates, nitrates, and sulphates, though more complete data will be necessary to determine the exact relations and perhaps the significance of the different oxygen content of the acid radicals.

Silicate.—The circle[1] marked *Si* represents the position found for a band in enstatite ($MgSiO_3$).

II. THE RÔLE PLAYED BY OXYGEN IN THE SELECTIVE REFLECTION CHARACTERISTIC OF CARBONATES, NITRATES, SULPHATES, AND SILICATES

In this connection a somewhat broader phase of the subject presents itself, and we ask, Do the bands in these different acid radicals have any relation to each other?

The selective reflection of the salts (given in Table III) with bases having nearly the same molecular weight is compared. In Fig. 9 the weights of the elements combined in the acid radical with three molecules of oxygen are plotted as ordinates and as abcissae the wave-lengths of the first reflection bands. A straight line fits the results remarkably well, especially when one recalls that the lower atomic weight of magnesium is partly responsible for the highest point lying toward the short waves, and when one takes into account the difference in the values obtained by independent investigators for the KNO_3 band shown in the same figure (Fig. 9).

TABLE III

Substance	Chemical Composition	Atomic Weight of Base	Weight with 48 g of O	Position of Band	
Calcite	$CaCO_3$	39.7	12g of *C*	6.6 μ	
Potassium Nitrate	KNO_3	38.9	14 *N*	7.15*	7.05†
Anhydrite	$CaSO_4$	39.7	24 *S*	8.6[1]	
Enstatite	$MgSiO_3$	24.2	28 *Si*	9.1[1]	

* Coblentz, *loc. cit.* † Pfund, *loc. cit.*

A change in the weight of the element combined with equal amounts of oxygen in the acid radical produces a much larger shift in the position of the reflection maximum than is produced by the same change

[1] Coblentz's data in Fig. 8 shown by circles, Pfund's by crosses.

in the atomic weight of the base. This is in agreement with the chemist's views regarding the relative strength of the bond existing in the two positions. Similar considerations suggest that peculiarities of the individual elements other than the differences in their atomic weights may be found to exert a stronger control when within the acid radical

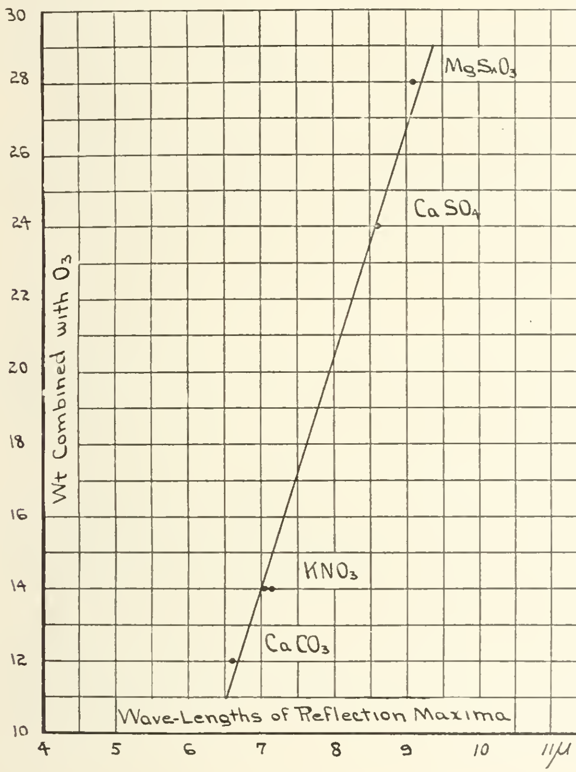


FIG. 9

than they do in the base, and similarity or dissimilarity of its relation to the oxygen in the acid radical must be carefully studied.

In this we may have a clue to a general method by means of which chemical formulae may come to have a more definite and wider dynamical meaning than they now do. At present, atomic relations within the molecules of a solid can only be inferred from evidence gained primarily from solutions and gases.

From the foregoing results it appears that there is a regular shift in the reflection bands, characteristic of a given acid radical, with a change in the atomic weight of the base with which it is combined; and second, that the active and characteristic element in the carbonic, sulphuric, nitric, and silicic acid radicals is oxygen. A change in the atomic weight of the element, combined *directly* with the *oxygen* in the acid radical, is far more potent in shifting the wave-length of the reflection band, than the same change in the atomic weight of the base, which is *indirectly* combined with the oxygen.

To establish the second hypothesis on as firm a footing as the first now rests, it may be necessary to give to salts of other acids the same systematic study which the carbonates have received, and in doing this the writer is at present engaged.

SUMMARY

1. The reflection curves for all the carbonates examined show between 4 μ and 15 μ three, and only three, bands of marked reflection.

2. The bands fall into three separate and definite spectral regions, which are distinct from the regions where the salts of other acids, so far as known, show reflection maxima.

3. With few exceptions, an increase in the atomic weight of the base causes a shift of all three reflection maxima toward long waves by an amount roughly proportional to the change in atomic weight of the base.

4. No regular displacements traceable to the chemical group to which the base belonged were observed, nor does any simple relation appear between the wave-lengths of the three bands in carbonates.

5. Combining with the data on carbonates the scattered observations on nitrates, sulphates, and silicates, the tentative hypothesis has been made that the oxygen atom is the one chiefly responsible for the marked reflection observed.

6. The results presented in the present paper suggest a new and far-reaching method by which it may some time be possible to express the dynamical relations existing between the separate atoms of a molecule, and thus the present conception of chemical bonds and linkages be given a broader significance.

In conclusion, the author wishes to thank Professor E. F. Nichols,

who suggested the problem and directed the work, for the daily interest shown; but he would like especially to express his deep appreciation of the profit he has derived from frequent discussions during the progress of the work concerning its broader relations.

Phoenix Physical Laboratory
Columbia University
August 1907

ADDENDUM

Since the foregoing paper went to the printer my attention has been called to a short paper in the *Jahrbuch der Radioaktivität und Elektronik* (4, 132, 1907) by Dr. W. W. Coblentz in which, after reporting the analysis of the first reflection band in eight carbonates and the reflection and absorption bands between 4μ and 9.4μ in seven sulphates, diagrams are given and the following conclusions drawn:

> Im ganzen genommen reichen die dargestellten Ergebnisse hin, um nachzuweisen, dass das Molekulargewicht tatsächlich die Lage des Maximums beeinflusst; es ist aber zu beachten, dass die Verschiebung durch das metallische Atom oder "Ion" verursacht wird an welche die Atomgruppe gebunden ist. Andererseits wird, nach früheren Ergebnissen, die Lage des Maximums durch die Anzahl der Atomgruppen nicht beeinflusst. Dasselbe gilt auch für das Kohlenstoffatom an sich. Die Atomgruppen sind mithin als die Ursache gewisser charakteristischer Absorptions- und Reflektionsbanden zu betrachten; die Lage dieser Banden aber wird durch das Atomgewicht des metallischen Atoms bestimmt, mit dem vereinigt die Atomgruppe die Verbindung bildet.

Dr. Coblentz's paper is dated March 22, 1907. Before this, a considerable portion of the data here presented had been gathered.

L. B. M.

AN ABSOLUTE SCALE OF PHOTOGRAPHIC MAGNITUDES OF STARS

By J. A. PARKHURST and F. C. JORDAN

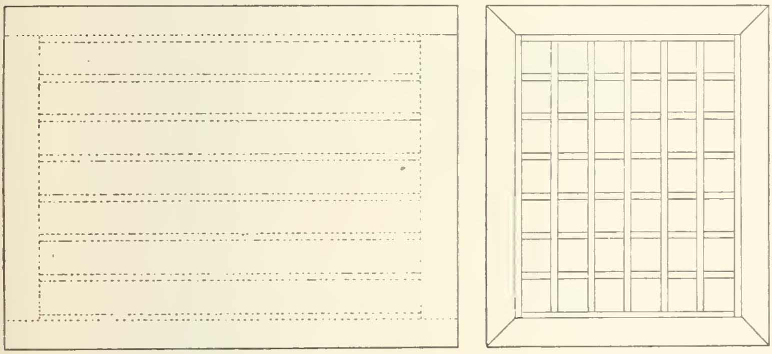
The determination of star-magnitudes by the method of measurement of the opacity of the silver deposit on extra-focal images, makes it possible to obtain an "absolute" scale; that is, the effect on the plate of lights differing by a known ratio can be determined by laboratory experiments. If the results obtained by this method were no more accurate than those given by indirect methods (such as the use of a number of stars of known magnitude on each plate) it would still be valuable as a check on those results. As a matter of fact, the opacity-measure of extra-focal images yields results of somewhat greater precision than is usually obtained by other methods. Added importance thus attaches to the correct determination of an "absolute" scale.

The method used in Europe of impressing on each plate, besides the ordinary image of a star, one formed through a wire grating or "Gitter," has its disadvantages, some of which are avoided by the method about to be described, which is very simple in theory and only requires the observance of suitable precautions in order to yield results of considerable accuracy.

The procedure is to illuminate certain areas of a plate simultaneously by lights differing in intensity by a known ratio. In this way the time element, or the truth of the so-called "law of reciprocity," does not enter the problem; and, as we are not dealing with the diameter of star images, the disturbing effect of any change of the source of illumination, or in the path of the rays, need not be considered.

To obtain the desired illumination a sensitometer box was used, shown in Fig. 1, eight inches long, holding a 4x5 plate at each end. Running lengthwise of the box are 42 light-tight cells, seven inches (18 cm) long and one-half inch (13 mm) square. One end of this system of cells was covered by a metal plate pierced with a hole opposite the center of each cell. When this end of the box was uniformly illuminated, the amount of light passing through each cell was fixed by

the diameter of the hole. To insure uniformity of illumination, two or more pieces of ground-glass, one inch apart, were put between the source of light and the box. A sensitive plate placed at the other end of the box will be blackened in squares corresponding to each cell, the opacity of the deposit depending on the amount of light admitted by the hole in the metal plate. Fig. 2 (Plate XI) shows a specimen



Side Elevation   End Elevation

FIG. 1.—Sensitometer Box

plate, No. 47 in the series taken with metal plate *D*, on which only the 20 inner cells were used. Table I gives the numerical data for metal plate *D*.

TABLE I

No.	Diam.	Relative Area	Δ log Area	Δ Mag.	No.	Diam.	Relative Area	Δ log Area	Δ Mag.
1....	1.035	1.071	0.000	0.000	11....	2.639	6.963	0.813	2.033
2....	1.107	1.225	0.058	0.146	12....	2.827	7.992	0.873	2.182
3....	1.212	1.469	0.137	0.343	13....	3.076	9.462	0.946	2.366
4....	1.330	1.769	0.218	0.545	14....	3.599	12.953	1.083	2.707
5....	1.535	2.356	0.342	0.856	15....	3.757	14.115	1.120	2.800
6....	1.633	2.667	0.396	0.991	16....	4.186	17.523	1.214	3.035
7....	1.841	3.389	0.500	1.251	17....	4.647	21.586	1.304	3.261
8....	1.982	3.928	0.564	1.411	18....	5.002	25.020	1.368	3.421
9....	2.116	4.477	0.621	1.553	19....	5.407	29.236	1.436	3.590
10....	2.391	5.717	0.727	1.819	20....	6.271	39.326	1.565	3.912

In this table the diameters are expressed in millimeters, the "relative area" is the square of the diameter, the "Δ log Area" is the difference between the log area of each hole and that of hole No. 1, and finally the "Δ Mag." is the Δ log area divided by 0.4. This last column

will therefore represent the relative star-magnitudes of the lights passing through each cell.

For the measurement of these opacities and the star plates on which the method has been applied, a Hartmann "mikrophotometer"

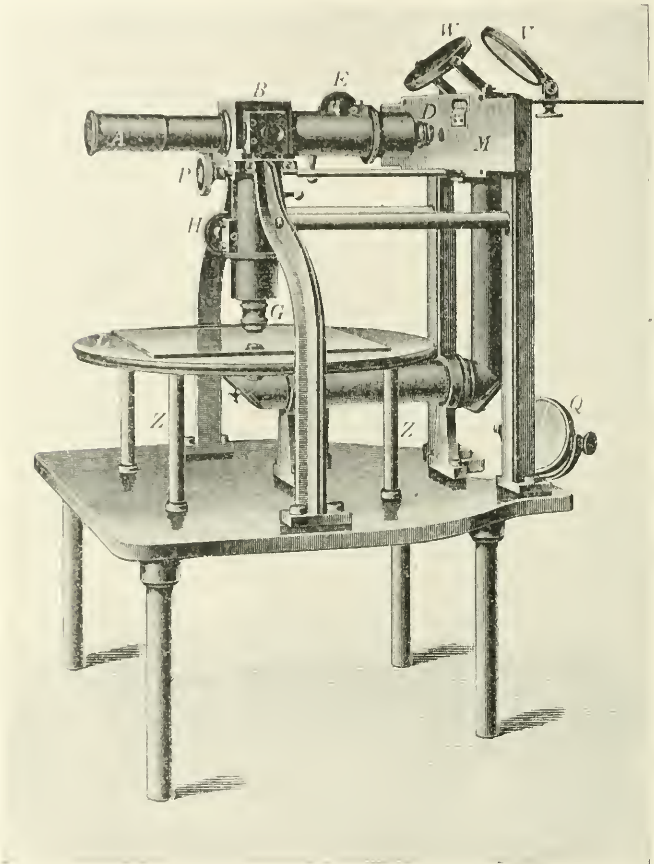


FIG. 4

has been used. The purchase of this fine instrument was made possible by a grant from the Rumford Committee of the American Academy, and acknowledgment is here made of the aid thus kindly furnished for this work. A perspective view of the instrument is shown in Fig. 4 and a full description will be found in this journal,

10, 321, 1899. As there described, the method of measurement is to match the opacity with a photographic wedge. The wedge so far used is a portion of a plate furnished by Professor E. C. Pickering and numbered by him "E 5862." This is evidently one of the plates made by Mr. E. S. King[1] and similar to that used by J. A. Parkhurst in the equalizing wedge-photometer.[2]

It will now be evident that if a plate such as Fig. 2 be measured in the photometer, the absorption-curve of the wedge will be given directly in stellar magnitudes. Then if star images are taken out of focus, the effect of stars of different magnitudes in illuminating the image surfaces will be comparable with the light passing through holes of different diameters. Therefore the scale of the photographs will be "absolute" in the sense that it is derived from laboratory experiments.

Among the precautions used to insure consistent results the following may be mentioned:

1. The same brand of plates, Seed 27, were developed with hydroquinone developer of the same constitution for ten minutes at $+20°$ C.

2. A test was made of the effect of exposure temperatures between $-2°$ and $+17°$ C. It was found that the development factor (the maximum slope of the absorption-curve) was not affected between these limits. Changes, if any, were confined to the thinnest and densest squares, and these were not used in the measures.

3. A test of different colors of light gave a like negative result. Incandescent lights burning above and below candle-power, daylight, and magnesium light gave the same absorption-curve. It should be noted, however, that for ordinary exposures the sensitiveness of the Seed plate extends only to about the $H\beta$ line, so that this test merely showed the effect of light of shorter wave-length than $H\beta$.

4. Changes in the exposure time between ten seconds and thirty minutes had no effect on the curve. Had this test given a different result the method could not be used on the stars, since the exposure times must vary according to the faintness of the stars required.

5. Negatives made on plate glass gave much more accordant results than those on ordinary glass. Local errors, due to the thickness of

[1] *Annals of Harvard College Observatory*, 41, 237.

[2] *Astrophysical Journal*, 13, 249, 1901; *Researches in Stellar Photometry*, 8.

the emulsion, were quite noticeable in the ordinary glass, but almost disappeared on plate glass.

6. Four metal plates, *A*, *B*, *C*, and *D*, each with a different arrangement of holes, were used with various exposure times, and the box was frequently inverted, so that the light from a particular hole, or cell, would fall at different parts of the absorption-curve. There were no systematic differences found from the various metal plates or the different positions of the box. Fig. 5 shows the final absorp-

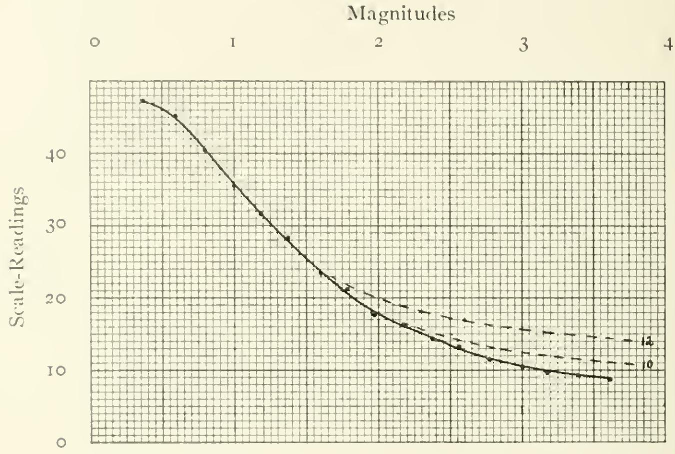


FIG. 5.—Absorption-Curves

tion-curve used in the reductions. It is derived from the measures of twenty plates, four of them being on plate glass, all taken with metal plate *D*.

7. The effect of a supplementary exposure (such as would come from "sky fog") was very noticeable and was thoroughly investigated. Strips five-eighths of an inch (15 mm) wide were exposed across the plate, fogging half of each square, so that the clear and the fogged part could be measured. This arrangement is shown in Fig. 3. Plates were fogged before, during, and after the main exposure, giving the same result. The effect of a very slight fog was noticeable on the thin squares, but it was not measurable on the denser squares, even when the fogging was as great as would result from three hours' exposure in the camera to a dark sky. It is therefore evident that the star plates cannot all

be reduced with the same absorption-curve, but the amount of fogging in the film can be readily measured with the photometer, and in practice each plate is reduced with a curve corresponding to the fog. The broken lines in Fig. 5 show the curves corresponding to fog readings of ten and twelve on the photometer scale.

The stellar plates on which this method is applied, have been taken with a Zeiss doublet of 14.5 cm aperture and 81.4 cm focal length. Most of the plates have been taken 7 mm inside the focus, giving a star image 1 mm in diameter. At this setting the illumination of the image is very nearly uniform, so that it can be measured in the photometer as accurately as a perfectly uniform area. With a disk of this diameter ten minutes' exposure gives a measurable image of a seventh magnitude white star, though a sixth magnitude star can be measured with greater accuracy, since the opacity falls at a steeper part of the absorption-curve. As tests and illustrations of the method, results of the measures of the *Pleiades* and a number of variable stars of short-period and *Algol* type will be given.

Pleiades

Of the countless measures of the *Pleiades*, the best for comparison with the present method seem to be those made by Schwarzschild,[1] both from the excellent quality of the work and the fact that they were measures of extra-focal photographic images, reduced by means of the visual magnitudes of the white stars. Four exposures on the *Pleiades*, of 1, 3, 10, and 25 minutes respectively, containing 19 stars, were measured and the absorption-curve of the wedge was platted, using Schwarzschild's magnitudes given in Table 14 of the work cited. Table II gives the differences between this curve and that derived from the standard sensitometer squares, expressed in magnitudes, for each 5 mm of the scale, in the sense, Sch.–P.

TABLE II

Scale	Δ Mag.	Scale	Δ Mag.
45	−0.20	25	0.00
40	−0.08	20	+0.01
35	−0.01	15	+0.01
30	0.00	10	+0.13

[1] *Publicationen der v. Kuffnerschen Sternwarte,* 5, C.

The curves are almost identical between scale-readings 12 and 37, but there are systematic differences at both ends of the scale. These are probably due to the fact that readings on very thin images, below 12, are not reliable; further, the normal point at 42 depends on only two stars, and above that point the images are too dense for good measurement. The portion of the scale which can be used thus lies between 12 and 40, corresponding to 2.0 magnitudes. A very slight difference in opacity is readily recognized in the photometer, so that the average deviation of a single setting from the mean of three is between 0.1 and 0.2 mm, corresponding to a little more than 0.01 magnitude. From the above discussion it seems evident that within the limits mentioned the scale is correct, and the method is capable of yielding results of extreme accuracy over a range of about two magnitudes on a single plate. Certain useful lines of work are indicated, such as measurement of the light-curves of variables of the *Algol*-type and of short-period variables, especially those regarding whose changes there is conflicting evidence.

MINIMUM OF THE *Algol*-TYPE VARIABLE *U Ophiuchi*

Five plates were taken of the star, covering two minima. Fig. 6 shows the minimum platted from sixteen exposures on Plate 195 and

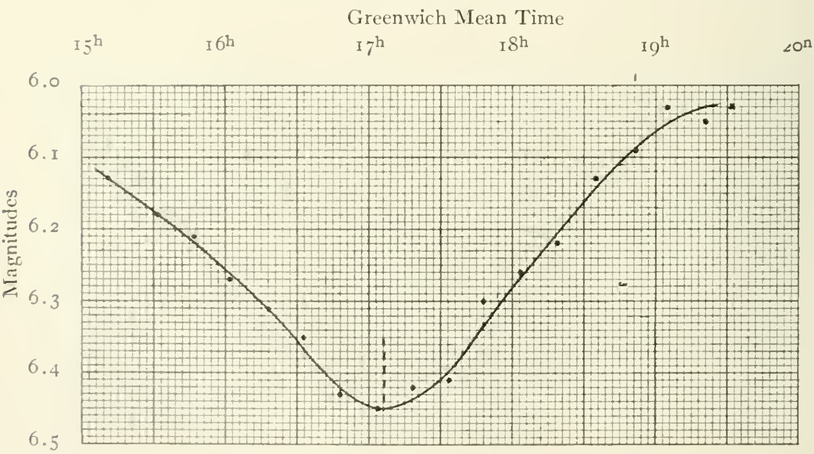


FIG. 6.—Minimum of *U Ophiuchi*, 1907 June, 13

two on Plate 196. The largest residual from the curve is 0.03, the average ±0.014 magnitude. The total exposure on Plate 195 was 152 minutes, causing a sky-fog a little too dense for the reduction-curves; therefore the range shown is too small by 0.10 or 0.15 magnitude. The shape of the curve and the time of minimum are, of course, unchanged. The time of minimum is $11^h\ 6^m$ Central Standard Time, or $17^h\ 6^m$ G. M. T. Reduced to the sun this becomes $17^h\ 14^m$. The correction to Hartwig's ephemeris in the *Vierteljahrsschrift* is $-1^h\ 0^m$. The correction to the ephemeris in the *Annuaire* is $+0^h\ 20^m$.

LIGHT-CURVE AND ELEMENTS OF *RZ Cassiopeiae*

This *Algol*-type variable was discovered by Müller and Kempf[1] who gave the elements of minimum 1906, May 24, $10^h\ 15^m + 1^d\ 4^h\ 40^m.8$ E. Its binary character is shown by spectrograms taken by Hartmann[2] at Potsdam and by Parkhurst with the Bruce spectrograph at this observatory.[3] Since the announcement of variability, eighteen plates of the region have been taken, containing fifty-eight exposures; covering besides the minimum the entire period. The comparison stars used are

B. D.	Potsdam Color	Potsdam Mag.	Spectrum	Adopted Mag.
F+67°224	GW	6.15	A	6.15
D+69.171	—	—	A	7.43

Special care has been taken to select white stars for standards in order that the visual magnitudes may be taken without correction. With this in view plates of the region have been taken with a Zeiss objective prism of 15° angle, used in connection with the same camera with which the extra-focal plates are taken. The scale is sufficient to show clearly the type of spectrum, and furnishes a more accurate indication of the star-colors than can be found in the *Potsdam Photometric Durchmusterung* or the *Draper Catalogue.* The strength of the K line in these spectra is an excellent criterion of the color. In white stars it is absent or very faint, while in spectra called *F* in the

[1] *Astronomische Nachrichten,* **171**, 357, 1906.

[2] *Astronomische Nachrichten,* **173**, 101, 1906.

[3] *Astrophysical Journal,* **25**, 59, 1907.

Draper Catalogue classification the K and H lines are about equal. These *F* stars have a photographic magnitude about $\frac{1}{2}^m$ fainter than the visual. The relation between color and spectral type is being investigated in this connection, and provisional results will soon be published in this journal.

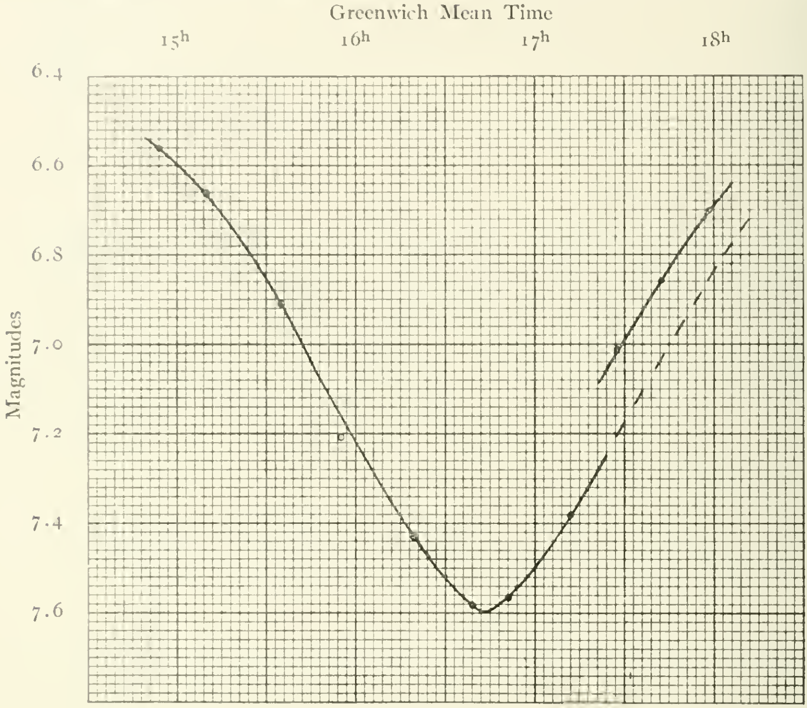


FIG. 7.—Minimum of *R Z Cassiopeiae*, 1907, Aug. 3

Fig. 7 shows the curve of minimum of 1907, Aug. 3, from Plate 210, having eleven exposures, the Greenwich Mean Times being 1907, Aug. 3 from 14^h 54^m to 17^h 58^m, showing a minimum at 16^h 44^m, which corrected to the sun is 16^h 42^m. It will be noticed that the last three exposures give points on a curve about 0.2 magnitude above the rest. This is due to the overlapping of these images with those of the star *B. D.* $+69^\circ_{.}180$, which lies 52′ north of the variable. The probable curve which the star would have followed, were it not for this overlapping, is shown in the broken line. Fig. 8 shows[1] a part of

[1] The cut is not a good representation of the plate.

Plate 210, including the comparison stars *F* and *D*, also the star marked *E*, which is *B. D.* +68°200 = 155. 1906 *Cassiopeiae*. The plate-holder is carried by a slide moved by a screw with a large head. The plate was moved one turn of this screw, $\frac{1}{20}$ inch, between the exposures, except

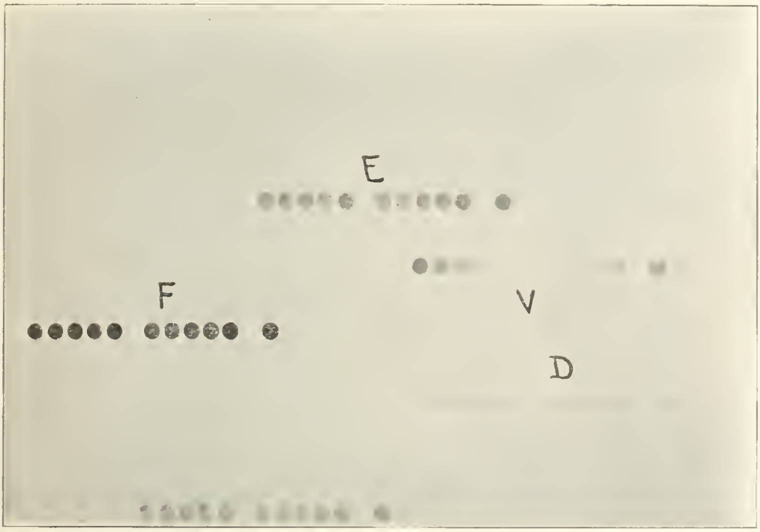


FIG. 8.—Extra-focal Images Showing Minimum of *R Z Cassiopeiae*

that two turns were used, after the fifth and tenth exposures, for aid in identification.

The entire light-curve of this star has been covered by eighteen extra-focal plates with fifty-eight exposures. Six of these plates occur in the minimum phase, and they have been combined with four focal plates taken by Jordan with the twenty-four inch reflector, to form a mean curve. Together they give the following normal points:

Time from Min.	Mag.	Time from Min.	Mag.
$-0^d.106$	6.47	$+0^d.017$	7.41
−0.072	6.64	+0.026	7.29
−0.054	6.84	+0.035	7.04
−0.030	7.25	+0.043	6.93
−0.009	7.55	+0.070	6.62
+0.002	7.64	+0.095	6.47
+0.014	7.61		

A smooth curve through these points gives the following mean curve

T.	Mag. Before	Mag. After	T.	Mag. Before	Mag. After
0^d00	7.64		0^d06	6.77	6.72
0.01	7.55	7.56	0.07	6.66	6.62
0.02	7.40	7.36	0.08	6.58	6.55
0.03	7.22	7.17	0.09	6.52	6.49
0.04	7.05	6.99	0.10	6.48	6.46
0.05	6.90	6.84	0.11	6.44	6.44

Fourteen plates with twenty-eight exposures give the following points in the normal light of the star:

Time after Min.	Mag.	Δ Mag. from 6.43	Time after Min.	Mag.	Δ Mag. from 6.43
0^d111	6.45	+0.02	0^d673	6.45	+0.02
0.174	6.47	+0.04	0.794	6.46	+0.03
0.299	6.40	−0.03	0.893	6.38	−0.05
0.520	6.44	+0.01	1.044	6.43	0.00

We may draw these conclusions from the above results:

1. The normal light is 6.43, the minimum 7.64, range 1.21 magnitude.
2. There is no trace of a secondary minimum.
3. The duration of the eclipse is 0.23 day, $=5^h\ 32^m$.
4. The minimum is sharply defined.
5. The maximum rate of change is 0.73 magnitude per hour.

The period seems to be about 22^s longer than that given by Müller and Kempf in the place above cited. The plates taken here are best satisfied by the elements:

Minimum = J. D. $2417355.427 + 1^d.195258$ E.

Following is a comparison of the residuals from our plates with the two values of the period.

Plate	Minimum Observed	Red. to Sun	Corrected Min.	Julian Day	Residuals, O.−C. M. and K. P=1.1950	Residuals, O.−C. P. and J. P=1.195258
	1906					
R 69.....	Aug. $14^d\ 21^h.5$	$-1^m.2$	$14^d\ 21^h.5$	7437.896	+0.014	+0.002
R 83.....	Aug. 31 $15^h\ 7^m$	+0.2	31 15 7^m	7454.630	+0.018	−0.003
R 104....	Sept. 25 17 35	+2.7	25 17 38	7479.735	+0.028	+0.001
R 175....	Dec. 19 14 0	+4.8	19 14 5	7564.587	+0.035	−0.010
	1907					
UV 365...	Aug. 3 16 44	−2.2	3 16 42	7791.696	+0.094	0.000
R 406....	Sept. 21 16 42	+2.2	21 16 44	7840.697	+0.100	−0.004

THE SUSPECTED VARIABLE *32 Cassiopeiae*

This star received the provisional notation 186.1904, and later the notation *RU Cassiopeiae*, but most observers have found it constant. A previous report by the writers[1] from 72 exposures on four reflector plates stated that the star was found constant at 0.03 mag. fainter than the neighboring white star $+63° 149$. As the extra-focal method seems particularly well adapted to settle such disputed questions involving slight variation, Plate 223 was taken of this field on 1907, Sept. 13, having eight exposures covering four hours.

Four comparison stars were measured, as follows:

Star	B. D.	PDM		Adopted Mag.
		Color	Mag.	
C..........	+63 149	*GW*−	5.81	5.83
D..........	+63° 147	....	....	7.45
E..........	+63° 176	*GW*	6.64	6.55
F..........	+65° 115	*GW*−	6.10	6.15

Measures of *32 Cassiopeiae* on this plate gave

G. M. T.	Mag.	Δ from 5.86
14^h 41^m	5.86	0.00
15 19	5.87	0.01
15 30	5.86	0.00
16 2	5.86	0.00
16 19	5.84	0.02
17 2	5.85	0.01
17 39	5.86	0.00
18 34	5.85	0.01
Means	5.86	±0.006

It seems therefore to be reasonably certain that at the present time the star is not varying.

YERKES OBSERVATORY
September 1907

[1] *Astrophysical Journal*, 23, 88, 1906.

TEMPERATURE CONTROL FOR SILVERED SPECULA

By HEBER D. CURTIS

In recent years, with the growing use of silvered glass specula in astronomical research, the subject of focal changes in such systems due to changing temperature has assumed considerable importance.

Professor Keeler, to whom, more than to any other, is due the establishment of the great power of reflectors in astronomical photography, has described some difficulties of this nature in his well-known paper on the Crossley reflector.[1] He did not consider that the changes which he found in a long exposure were due to temperature effects, but rather to the fact that the axis of the mirror, through flexure effects in the mounting, wandered irregularly over the field. As the field has considerable curvature for this angular aperture (1:5.8) the effect of a change in the focus was produced. His explanation that the focal changes in the Crossley reflector were thus inherent in the method of mounting, rather than in the mirror itself, is borne out by the experience of Dr. C. D. Perrine, who finds that with the new and greatly improved mounting of this instrument,[2] no appreciable change of focus is experienced which can be attributed to temperature effects.

Quite recently Director Hale has described similar difficulties in the use of the Snow horizontal telescope at the Carnegie Solar Observatory on Mount Wilson.[3] In this case the mirror is twenty-four inches in diameter with much smaller angular aperture, 1:30. The focal changes in this instrument have at times amounted to as much as twelve inches, and on one occasion the difference in focus was three inches for opposite limbs of the sun. Considerable improvement has been brought about by the use of electric fans to keep the air about the mirror in circulation, by taking photographs quite early or quite late in the day, and by carefully screening the mirrors till just before

[1] *Astrophysical Journal*, 11, 325, 1900.

[2] *Lick Observatory Bulletin*, 3, 124, 1905.

[3] *Astrophysical Journal*, 23, 6, 1906; *Contributions from the Solar Observatory*, No. 4.

the moment of exposure. In the Snow telescope the phenomenon is doubtless complicated by the fact that there are two additional plane mirrors in the coelostat train. That a due proportion of the effect may rest in the flats is borne out by the experience of Professor Barnard at the Sumatra eclipse. In using a camera of 61.5 feet focal length he found an occasional variation of about six inches which he attributed to a change in the figure of the coelostat flat due to the action of the sun's rays.

In the work of the D. O. Mills expedition to the Southern Hemisphere Professor W. H. Wright found similar small focal changes in the 37-inch Mills reflector, due to temperature effects. The forthcoming report of the results secured by the expedition during the first three years will contain Professor Wright's data on these points, together with a theoretical discussion of the causes. For the purposes of this paper it will be sufficient to repeat here the main facts with regard to the instrument, which is of the Cassegrainian form.

The great mirror is of very clear glass, free from noticeable bubbles or defects, and has a clear aperture of 36.56 inches (92.9 cm). Its focal length is 17.46 feet (5.49 cm). A hyperbolic secondary mirror gives to the instrument an equivalent focus of 55.4 feet (16.89 meters). The disk of the large mirror is 5.5 inches (14 cm) in thickness at the center and is pierced by a central hole 4.87 (12.4 cm) in diameter. The cell is of cast iron about half an inch thick, the bottom of which has an opening 8.5 inches (21.6 cm) in diameter, which was ordinarily kept closed with a cast-iron filler having a two-inch aperture. Aside from this opening in the back of the cell, and the few small holes for the adjusting screws of the mirror support, the only other ventilation about the mirror was provided by a door six inches square in the side of the cube above the mirror.

Professor Wright found a progressive focal change of fifteen to twenty-five millimeters occurring in the first half of the night. This change was always in the direction of increasing focal length, it being necessary to lengthen the focus of the telescope gradually throughout the first four or five hours of a night's work. These changes Mr. Wright attributes to a more concave form of the mirror brought about by the fall in temperature.

When the writer was appointed to continue for five years the work

in the Southern Hemisphere, for which Mr. Mills had generously made provision, it was decided, with the cordial support of Director Campbell, to try the effect of artificial cooling of the primary mirror in the effort to do away with these focal changes.

As a preliminary, the ventilation of the mirror in its cell was improved. The mirror cover, which had formerly rested nearly in contact with the glass, was moved fourteen inches up the cube; the small window in the cube was enlarged to six by sixteen inches and a similar window cut on the opposite side. Six holes, each 5.2 inches in diameter, were cut in the back of the cast-iron cell. The use of the iron filler for the central opening in the cell was discontinued. The area of the ventilating apertures at the back of the cell is thus about one-sixth of the area of the mirror.

During the past observing season a record has been kept of all the focal changes occurring in the mirror system. It cannot be said that the increased ventilation has in itself had much effect on the focal variations. These are perhaps a little smaller than before, averaging about twelve to fifteen millimeters under normal observing conditions. It is probable, also, that a condition of equilibrium is reached somewhat earlier, generally by four hours after sunset. Under normal summer observing conditions on Cerro San Cristobal a drop of 5° or 6° C. is experienced between three and eight P. M., followed by a slowly and generally very regularly decreasing temperature till dawn. In the less settled weather of fall and winter the daily range is generally smaller. The phenomena connected with the response of the mirror to the fall in outside temperature seem to be quite complex; many factors enter into the adjustment of the mirror to its condition of equilibrium, particularly the circulation of air in the dome and about the telescope. From a comparison of the observed focal ranges with the temperature records, it has not been possible to deduce any accurate relation between the two. Not infrequently a daily range of 2° C. will produce as great focal changes as a range of 6°. The rapidity with which a temperature change occurs seems to be of greater effect than the actual amount of the change. Neither has it been possible to establish that the focus of the system, when equilibrium has been reached, is different for different temperatures. With an irregular temperature-curve accompanying poor observing

conditions, the focal changes of the system are themselves quite erratic; in this class come the infrequent focal changes sometimes observed in the latter half of the night. As a rule, however, the focal changes between midnight and dawn are entirely absent.

Professor Wadsworth and Professor Ritchey have recommended the silvering of the back of mirrors to avoid such temperature effects. This plan has been tried with this mirror, but without appreciable effect on the focal range.

That the focal range has its origin entirely in the large mirror is proved not only by the results with artificial cooling to be given later, but also by focal tests of the primary on ten nights with an inclined photographic plate placed at its focus. On two of these nights with bad observing conditions and gusty wind the focal behavior was quite erratic; on the other nights a progressive focal range exactly parallel to that of the system was found, ranging from 1.2 to about 2.2 mm per night. The focal range of the Cassegrainian system is 10.1 times that of the primary, being the ratio of the squares of the two focal lengths. Using this multiplying factor we find a satisfactory agreement between the results of these tests and the focal ranges of the complete system. On two nights focal trails were made in quick succession at the focus of the primary, using alternately the central portion of the mirror and the outer zone. These tests showed that in the first part of the night the focus of the outer zone was shorter than that of the inner portion by about 1.2 mm, a difference which vanished in similar tests made at 3 A. M. Insulating the hole at the center of the primary with blanketing has not reduced the focal range.

The method of artificial cooling adopted is that of refrigeration by anhydrous ammonia. The machine was made by the Brunswick Refrigerating Company, of Brunswick, N. J., and is the smallest size of their regular commercial line of self-contained refrigerating plants which they manufacture for isolated cooling equipments. It is what is designated on their scale as a one-hundred-pound machine, i. e., its capacity is approximately that equal to the melting of one hundred pounds of ice per day; and it can, in addition, make ten pounds of ice per day. The machine occupies approximately six by two and a half feet of floor space, and requires a one H. P. motor to run it and

the small pump used for circulating water through the condensing system.

The operation of the machine is, in brief, as follows: liquid anhydrous ammonia is allowed to expand from its reservoir into the cooling coils, an automatic expansion valve providing that the pressure in the cooling system shall not rise above twenty pounds to the square inch. From the cooling coils the gaseous ammonia is withdrawn by the ammonia pump, compressed to a pressure of from one hundred and fifty to two hundred pounds, depending upon the external temperature and the temperature of the water in the condenser; the water circulating through the condenser takes up the heat produced by the condensing of the gas, so that when it reaches its reservoir again, it is about at the temperature of the outside air liquefied, at least in part, and ready to pass again through its cycle of alternate expansion and compression. The machine is entirely automatic in its action, it being necessary only to turn on the water circulation, open two valves, and start the motor.

As installed on Cerro San Cristobal the refrigerating machine is located in the small workshop, at a distance of forty-eight feet from the telescope pier to one side of which the cooling coils are permanently attached, being insulated from the pier by a layer of wood and two of heavy felt. These coils are of one-inch iron pipe, occupy a space three feet by two feet by six inches, and are connected with the refrigerating machine by strong iron pipe of about one-quarter-inch bore, the pipe being carefully insulated with cork or felt insulation, and all joints carefully soldered. When the mirror is being cooled, the telescope is placed in a vertical position and a removable wooden case rolled into position which is so arranged that the fastening of a few clips completely insulates from the outside air the interior of the case, containing the spectrograph, the mirror, and the lower half of the cube. The case itself is insulated within with thick felt and contains approximately eighty-five cubic feet, making no deduction for the spectrograph, mirror, or iron-work of the telescope. Two electric fans blow the cold air from the coils up so as to circulate freely around the mirror through the holes in the cell and in the cube. A double glass window allows readings to be taken on a thermometer placed inside the cube with its bulb close to the edge of the mirror. The

drop in the mirror temperature is slow for the first half-hour, owing to the fact that all parts of the piping and case must be cooled; later the drop is more rapid and no difficulty is found in lowering the temperature at the mirror from 5° to 7° C. in a run of one and a half hours.

The procedure which has been found to give the best results is to start the refrigeration about two and a half or three hours before sunset. After the thermometer at the mirror shows a fall of 5° or 6° C. the machine is stopped and the case removed at about forty minutes before sunset; at this time the outside temperature is falling quite rapidly, and the temperature of the mirror, at least of its outer portions, is somewhat below that of the air. By half an hour after sunset, under usual conditions, the mirror has adjusted itself perfectly to its focus for the night. Frost gathers thickly on the cooling coils, but no evidence has been found of any moisture forming on the silver surface, even when the mirror is two or three degrees C. below the temperature in the dome. A thick shield of felt and blanketing protects the spectrograph and its prisms from getting too cold as a result of the direct radiation from the frost-covered pipes. The procedure of leaving the mirror to adjust itself to equilibrium for a short time before using seems to give better results than planning the cooling to end at the time of beginning work. The difficulty here is to stop just at the right time; unless this is done there are slight focal changes for an hour or two.

In its control of focal changes this method of artificial cooling has been found to be quite successful. Focal changes are as a rule entirely absent; when occurring they are quite small, being rarely more than five mm. Sudden changes in the night temperature still cause small focal changes. Perhaps an open-work construction of the cell and cube so as to give very free circulation about the mirror might reduce these changes still farther; fortunately the temperature-gradient under average observing conditions here is very regular. When the cooling is employed, tests of the focus at sunset almost invariably show it to be at the same point at which it was left at the end of work on the night before. Occasional mistakes are made in the amount of cooling required when clouds or unusual conditions have greatly reduced the daily temperature range. On such occasions, when the

mirror has been cooled to a temperature considerably too low, it is interesting to note that the progress of the focal changes is reversed, being in the opposite direction from that observed in the uncooled system.

There is no evidence that the artificial refrigeration affects the silver surface of the mirror injuriously.

THE D. O. MILLS EXPEDITION
Santiago, Chile, June 1907

ORBIT OF THE SPECTROSCOPIC BINARY θ *DRACONIS*

By HEBER D. CURTIS

The binary nature of this star ($\alpha = 16^h\ 0^m.1$; $\delta = +58°\ 50'$) was discovered by Director Campbell.[1] Its visual magnitude is given as 4.1; and the photographic, as 4.8. Its type is described as *F* and XIII*a* in the Harvard classifications and as II*a* by Potsdam. Its lines are of poor quality, rather diffuse, and not easy to measure. This is particularly the case when the star is somewhat underexposed; for this reason six plates were given only half-weight in the discussion, and one plate, that of August 8, 1899, was rejected. In the table are given the plates and the velocities upon which the determination of the elements was made. All the plates were measured by the writer at Mt. Hamilton; the last nine plates were taken with the remounted Mills Spectrograph, λ 4500 central; the others with the original Mills Spectrograph, λ 4340 central.

No.	Plate	Date, G. M. T.	Velocity	Weight
			km	
1	680 D	1898, Mar. 23.978	+15.5	
2	696 C	April 6.986	−30.2	
3	1215 C	1899, April 8.978	+12.0	
4	1220 D	10.851	−14.3	
5	1221 A	10.900	−12.8	
6	1237 B	May 1.843	−32.4	
7	1275 A	June 8.852	+ 9.0	
8	1291 B	18.812	+ 7.3	
9	1309 B	27.819	+12.0	
10	1317 A	July 4.810	−24.0	
11	1324 B	11.728	−27.0	
12	1351 A	25.710	+ 5.4	
12*a*	1375 A	Aug. 8.707	−16.8	Rejected
13	2486 B	1902, Aug. 11.729	−17.2	½
14	2515 B	20.788	− 7.8	
15	2540 C	Sept. 14.743	−23.8	
16	2720 A	1903, April 5.954	−32.1	
17	2723 A	6.936	+ 5.4	½
18	2734 D	9.020	−30.8	
19	2745 E	29.002	+15.8	
20	2752 B	30.017	−23.8	½

[1] *Astrophysical Journal*, 9, 311, 1899.

No.	Plate	Date, G. M. T.	Velocity	Weight
			km.	
21	2760 D	1904, May 4.997	+14.8	
22	2784 A	11.967	−15.3	½
23	2889 A	Aug. 12.781	−31.2	
24	3177 C	1904, Feb. 29.010	+13.9	
25	3210 F	April 12.012	−14.3	
26	3222 E	May 9.958	− 1.6	½
27	3223 B	10.721	+13.5	
28	3225 E	10.986	+ 6.6	
29	3226 A	11.722	−25.6	
30	3245 F	23.993	−23.4	
31	3340 A	July 18.745	−31.9	
32	3344 A	19.744	+ 5.6	½

Preliminary elements were computed graphically by the method of Lehmann-Filhés.[1] A first solution based on these preliminary elements gave the following values:

ELEMENTS I

$$\text{Period} = 3.0708 \text{ days},$$
$$e = 0.0162,$$
$$T = \text{J. D. } 2415368.772,$$
$$\omega = 103^\circ.472,$$
$$K = 23.39,$$
$$\mu^\circ = 117^\circ.2334,$$
$$\text{Velocity of system} = -8.45 \text{ km.}$$

From these elements an ephemeris was computed and differential coefficients derived; and from these, after including as factors for homogeneity

$$x = \delta V,$$
$$y = [1.6925]\delta T,$$
$$z = [4.4239]\delta\mu,$$
$$u = \delta K,$$
$$v = [1.3750]\delta\omega,$$
$$w = [1.3718]\delta e,$$

[1] *A. N.*, **136**, 17, 1894.

the following weighted equations of condition were formed:

No.	δV	δT	$\delta\mu$	δK	$\delta\omega$	δe	n
1....	$+1.000x$	$+0.022y$	$+0.020z$	$+0.996u$	$-0.038v$	$-0.187w$	$+0.253=0$
2....	+1.000	−0.440	−0.392	−0.894	+0.435	+0.648	−0.290
3....	+1.000	+0.448	+0.250	+0.885	−0.467	+0.654	−0.090
4....	+1.000	−0.887	−0.493	−0.352	+0.909	−0.128	+0.872
5....	+1.000	−0.913	−0.508	−0.259	+0.938	−0.141	+0.608
6....	+1.000	−0.194	−0.104	−0.984	+0.181	+0.164	−0.337
7....	+1.000	−0.553	−0.278	+0.808	+0.560	−0.985	−0.539
8....	+1.000	+0.779	+0.384	+0.615	−0.790	+1.000	+0.489
9....	+1.000	+0.448	+0.218	+0.885	−0.467	+0.654	−0.083
10....	+1.000	+0.772	+0.370	−0.640	−0.777	−0.909	−0.228
11....	+1.000	−0.632	−0.299	−0.755	+0.635	+0.924	−0.333
12....	+1.000	+0.838	+0.386	+0.533	−0.848	+0.981	+0.514
13....	+0.707	+0.686	−0.377	−0.182	−0.685	−0.193	−0.691
14....	+1.000	+1.000	−0.557	+0.063	−1.000	+0.362	−0.282
15....	+1.000	+0.728	−0.422	−0.689	−0.735	−0.955	+0.290
16....	+1.000	−0.287	+0.219	−0.959	+0.276	+0.356	−0.449
17....	+0.707	−0.514	+0.393	+0.449	+0.525	−0.638	−0.253
18....	+1.000	−0.278	+0.213	−0.962	+0.267	+0.337	+0.054
19....	+1.000	+0.260	−0.204	+0.960	−0.279	+0.298	+0.659
20....	+0.707	+0.477	−0.375	−0.523	−0.482	−0.698	+0.518
21....	+1.000	−0.027	+0.021	+0.996	+0.012	−0.284	−0.011
22....	+0.707	+0.704	−0.561	−0.090	−0.703	−0.007	−0.999
23....	+1.000	+0.001	−0.001	−1.004	−0.017	−0.233	+0.275
24....	+1.000	+0.121	−0.128	+0.988	−0.139	+0.014	−0.290
25....	+1.000	−0.908	+1.000	−0.279	+0.932	+0.702	+0.250
26....	+0.707	−0.629	+0.709	+0.227	+0.648	−0.290	−0.163
27....	+1.000	+0.281	−0.317	+0.954	−0.300	+0.341	−0.130
28....	+1.000	+0.738	−0.832	+0.663	−0.750	+0.992	−0.148
29....	+1.000	+0.680	−0.767	−0.736	−0.687	−0.986	+0.018
30....	+1.000	+0.700	−0.798	−0.717	−0.707	−0.975	+0.673
31....	+1.000	−0.209	+0.249	−0.980	+0.196	+0.196	−0.199
32....	+0.707	−0.533	+0.635	+0.422	+0.546	−0.608	+0.025

Whence the normal equations:

[aa]	[ab]	[ac]	[ad]	[ae]	[af]	[an]
+29.000	+ 2.623	−2.470	− 0.650	− 2.767	+ 1.119	+0.441
	+11.221	−3.064	+ 2.030	−11.374	+ 0.088	−0.441
		+6.751	+ 1.619	+ 3.097	+ 1.722	+0.020
			+17.224	− 2.086	+ 2.619	+0.194
				+11.533	− 0.146	+0.455
					+12.433	−0.325
						+5.755

The solution of these normal equations gave as corrections to Elements I:

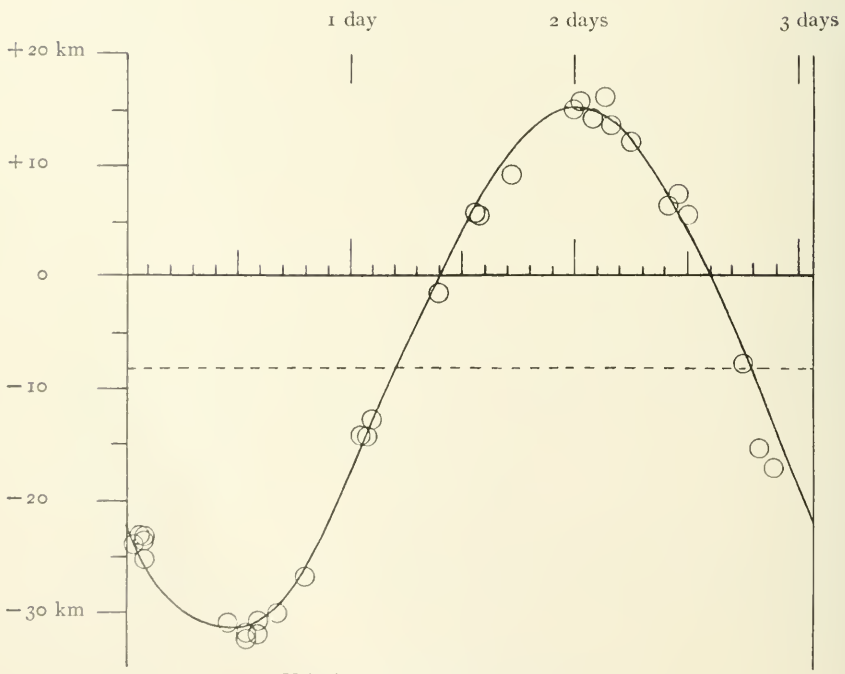
$$\delta V = +0.09 \text{ km},$$

$$\delta T = +0.190 \text{ days},$$

$$\delta\mu = -0.0000007,$$
$$\delta K = +0.077,$$
$$\delta\omega = +0.395 \text{ radians},$$
$$\delta e = -0.0021.$$

FINAL ELEMENTS

Period $= 3.0708 \pm 0.000032$ days,
$e = 0.0141 \pm 0.0166$,
$T =$ J. D. 2415368.962 ± 0.499 days,
$\omega = 126\overset{\circ}{.}112 \pm 58\overset{\circ}{.}6$,
$K = 23.47 \pm 0.324$,
Velocity of system $= -8.36$ km ± 0.30 km,
$a \sin i = 9{,}900{,}000$ km.
(pvv) Eph. $= 43.36$
(pvv) Equ. $= 43.24$



Velocity-Curve of θ *Draconis*

The probable error of a plate is 0.87 km. This is represented in the accompanying diagram of the velocity-curve and the observations by the radius of the small circles. The velocity of the center of mass of the system is given by the dotted line.

The residuals found from these elements are tabulated in the final table, together with a comparison of the change in the residuals secured respectively from the final ephemeris and by direct substitution in the equations of condition.

No.	Resid. O.−C.	Eph.−Eq.	No.	Resid. O.−C.	Eph.−Eq.
1..........	+0.65	−0.01	17.........	−1.36	+0.14
2..........	−0.74	−0.03	18.........	+0.27	−0.10
3..........	−0.20	−0.09	19.........	+1.82	−0.04
4..........	+2.16	+0.08	20.........	+2.01	−0.05
5..........	+1.40	+0.13	21.........	−0.13	+0.03
6..........	−0.83	−0.09	22.........	−3.94	−0.04
7..........	−1.78	+0.15	23.........	+0.86	−0.10
8..........	+1.40	−0.10	24.........	−0.83	−0.03
9..........	−0.19	−0.08	25.........	+0.46	+0.08
10..........	−0.65	−0.07	26.........	−1.05	+0.06
11..........	−0.92	−0.06	27.........	−0.36	−0.04
12..........	+1.45	−0.02	28.........	−0.37	−0.09
13..........	−2.74	−0.04	29.........	+0.04	−0.05
14..........	−0.82	−0.02	30.........	+1.85	−0.05
15..........	+0.70	+0.04	31........	−0.43	+0.11
16..........	−1.12	−0.04	32.........	−0.29	+0.02

THE D. O. MILLS EXPEDITION
Santiago, Chile, June 1907

ORBIT OF THE SPECTROSCOPIC BINARY *a CARINAE*

By HEBER D. CURTIS

The binary character of this star ($\alpha = 9^h\ 8^m.4$; $\delta = -58^\circ\ 33'$) was discovered by Professor W. H. Wright in the course of the work of the D. O. Mills Expedition to the Southern Hemisphere.[1] It is of visual magnitude 3.5, and the exposure time used has been fifty to sixty minutes under average observing conditions. It contains, in the part of the spectrum covered by the spectroscope of the Mills Reflector, only the following six lines:

λ 4267.316 *C*
4340.634 *H*
4388.100 *He*
4437.718 *He*, generally rather faint
4471.646 *He*
4481.400 *Mg*

The star is given as Type *B3A* in the Harvard classification, and the lines are of quite fair quality for this type of spectrum.

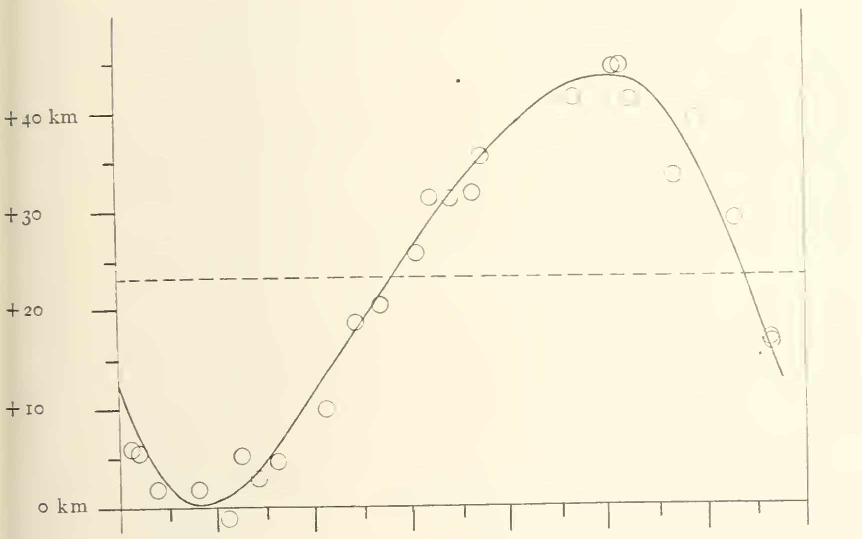
The orbit depends upon the following twenty-five plates:

No.	Plate	G. M. T.	Velocity	Measurer	O.−C.
			km		km
1.......	199 I	1904, Feb. 29.671	+ 5.5 + 6.0	Wright Palmer	−3.4
2.......	570 II	1905, Jan. 30.683	+32.6 +33.8	Wright Palmer	−5.1
3.......	588 II	Feb. 9.640	+ 9.2 +10.9	Wright Palmer	−3.2
4.......	607 III	22.617	+ 4.2 + 4.8	Wright Palmer	−1.4
5.......	617 II	Mar. 7.577	− 1.2	Palmer	−2.0
6.......	911 IV	1906, Mar. 30.578	+ 3	Curtis	+0.9
7.......	1071 III	1907, Jan. 15.789	+39.0	Curtis	+4.8
8.......	1077 II	19.814	+31.1	Curtis	+2.4
9.......	1084 II	21.755	+44.4	Curtis	+1.6
10.......	1102 II	25.810	+18.6	Curtis	+0.7
11.......	1107 II	26.786	+31.2	Curtis	−0.4

[1] *Lick Observatory Bulletin*, 3, 111, 1905; *Astrophysical Journal*, 21, 374, 1905.

No.	Plate	G. M. T.	Velocity	Measurer	O.–C.
			km		km
12.......	1128 IV	1907, Feb. 2.751	+31.8	Curtis	−2.4
13.......	1140 III	5.768	+16.2	Curtis	+1.6
14.......	1145 III	6.665	+ 2.0	Curtis	+1.8
15.......	1151 III	19.734	+ 1.9	Curtis	−2.1
16.......	1162 IV	Mar. 2.739	+41.3	Curtis	−1.3
17.......	1167 IV	4.736	+16.7	Curtis	+1.9
18.......	1183 III	14.625	+25.7	Curtis	−1.0
19.......	1188 III	16.634	+44.3	Curtis	+1.3
20.......	1195 III	19.574	+ 5.2	Curtis	+3.3
21.......	1199 II	23.528	+40.8	Curtis	−2.3
22.......	1208 IV	24.582	+28.8	Curtis	+3.4
23.......	1282 II	April 30.489	+20.4	Curtis	−0.9
24.......	1294 II	May 1.496	+35.2	Curtis	+0.1
25.......	1319 II	11.476	+ 5.7	Curtis	−1.2

An orbit was computed graphically from these values by the method of Lehmann-Filhés.[1] These elements were then tested and changed by varying the elements after comparison with the observed velocities



Velocity-Curve of *a Carinae*

[1] *A. N.*, 136, 17, 1894.

so as to give as close as possible a representation of the observations. The following elements resulted:

$$
\begin{aligned}
\text{Period} &= 6.744 \text{ days},\\
T &= \text{J. D. } 2416533.81,\\
\omega &= 115^\circ\!.84,\\
K &= 21.5,\\
\mu^\circ &= 53^\circ\!.380,\\
e &= 0.18.\\
\text{Velocity of system} &= +23.3 \text{ km.}\\
a \sin i &= 1{,}960{,}000 \text{ km.}
\end{aligned}
$$

A least-square solution would not be warranted by the number and character of the lines available for measurement.

In the accompanying figure I have plotted the separate observations with the orbit curve, the dotted line representing the velocity of the center of mass of the system. The actual residuals, in the sense observed minus computed, are given in the last column of the table. While some of these are rather large, they are not excessive when the character and number of the lines used is taken into account.

THE D. O. MILLS EXPEDITION
Santiago, Chile, June 1907

ORBIT OF THE SPECTROSCOPIC BINARY κ *VELORUM*

By HEBER D. CURTIS

The binary nature of κ *Velorum* ($\alpha = 9^h\ 19.0^m$; $\delta = -54°\ 35'$) was discovered by Professor W. H. Wright in the work of the D. O. Mills Expedition to the Southern Hemisphere.[1] The star is given in the Harvard classification as Type *B3A*; its visual magnitude is 2.6. The following six lines are the only ones usable in the portion of spectrum given by the spectrograph of the Mills Expedition:

λ 4267.316 *C*
4340.634 *H*
4388.100 *He*
4437.718 *He*
4471.646 *He*
4481.400 *Mg*

Of these lines the helium line at λ 4437 is generally faint and was not usable on a number of the plates. In addition to these lines exceedingly faint traces of a number of the oxygen lines of the β *Crucis* type are discernible on a few of the plates; these lines were never distinct enough to use.

The orbit depends upon the following twenty-seven plates:

No.	Plate	G. M. T.	Velocity	Measurer	O − C.
			km		km
1.......	216 I	1904, Mar. 6.739	+70.0 +66.8	Palmer Wright	+2.4
2.......	535 II	1905, Jan. 14.703	+12.9	Palmer	−2.0
3.......	602 II	Feb. 20.651	+65.7	Palmer	−0.7
4.......	618 III	Mar. 7.601	+53.3	Palmer	−3.6
5.......	1052 III	1907, Jan. 11.844	+58.6	Curtis	+2.3
6.......	1057 II	12.788	+57.9	Curtis	−1.1
7.......	1065 II	14.829	+58.5	Curtis	−2.7
8.......	1072 IV	15.824	+64.8	Curtis	+2.6
9.......	1085 III	21.788	+65.8	Curtis	−0.8
10.......	1129 II	Feb. 2.790	+62.0	Curtis	+0.4
11.......	1194 II	Mar. 19.534	−21.0	Curtis	−0.5
12.......	1198 II	20.556	−19.2	Curtis	+0.2

[1] *Lick Observatory Bulletin*, 3, 111, 1905; *Astrophysical Journal*, 21, 374, 1905.

No.	Plate	G. M. T.	Velocity	Measurer	O.-C.
			km		km
13.......	1200 III	1907, Mar. 23.570	−15.2	Curtis	+0.4
14.......	1207 III	24.545	−14.5	Curtis	+0.5
15.......	1256 III	April 20.591	+33.8	Curtis	+3.3
16.......	1264 III	25.572	+38.2	Curtis	−0.8
17.......	1270 III	26.555	+43.2	Curtis	+2.6
18.......	1283 III	30.480	+46.7	Curtis	−0.2
19.......	1300 II	May 5.494	+52.7	Curtis	−1.4
20.......	1364 III	June 14.466	+22.1	Curtis	+3.7
21.......	1366 II	19.463	+ 0.3	Curtis	+0.3
22.......	1377 I	22.470	− 7.6	Curtis	+1.0
23.......	1384 I	23.479	− 8.8	Curtis	+2.5
24.......	1390 I	24.463	−13.3	Curtis	+0.5
25.......	1397 I	26.457	−19.2	Curtis	−1.4
26.......	1402 I	July 1.451	−28.2 −29.9	Curtis Curtis	−4.8
27.......	1408 I	2.460	−23.9 −25.1	Curtis Curtis	+0.2

A preliminary orbit was computed graphically from these values in accordance with the method of Lehmann-Filhés.[1] Then a number of sets of elements were tested by comparison with the observations, slight changes being made in the values given by the graphical solution. The resulting orbit which best satisfies the observations is as follows:

ELEMENTS OF κ *VELORUM*

Period = 116.65 days,

$e = 0.19$,

$K = 46.5$,

$T =$ J. D. 2416459.00,

$\omega = 96^\circ\!.23$.

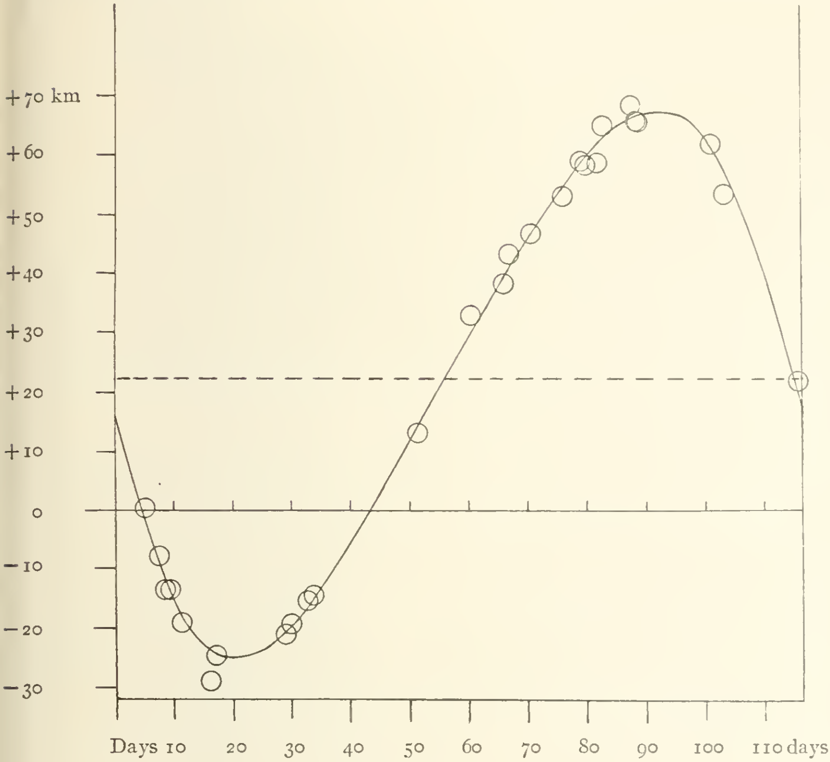
Velocity of system = +21.9 km,

$a \sin i = 73{,}200{,}000$ km.

These elements are represented by the curve of the accompanying diagram, where the dotted line gives the velocity of the center of mass of the system. The total range in the velocity is ninety-three kilometers. It is to be expected that future observations may change the

[1] *A. N.*, 136, 17, 1894.

value of the period slightly, as the observation period covers only about fourteen revolutions of the system. An ephemeris computed



Velocity-Curve of κ *Velorum*

from these elements gives the residuals, observed minus computed, which are tabulated in the last column of the table of observations.

The D. O. Mills Expedition
Santiago, Chile, August 1907

ORBIT OF THE SPECTROSCOPIC BINARY *α PAVONIS*

By HEBER D. CURTIS

The binary character of *α Pavonis* ($\alpha = 20^h\ 17^m.7$; $\delta = -57°\ 0'.3$) had been suspected by Professor W. H. Wright in Chile from preliminary measures of the first four plates taken, and has been independently discovered from the definitive reductions of the same plates made by Dr. S. Albrecht at Mt. Hamilton. The star is of the type *B3A*, similar to *α Carinae* and *κ Velorum*, though the lines are doubtless somewhat better than in these stars. Its visual magnitude is 2.0. Under fair observing conditions satisfactory plates can be secured in twenty-two to twenty-six minutes.

The following twenty-two plates form the basis of the elements derived in this paper:

No.	Plate	G. M. T.	Velocity	Measurer	O.–C.
			km		km
1.......	17 I	1903, Sept. 23.582	+ 2.0	Palmer	–0.9
2.......	333 II	1904, May 29.909	+ 9.5	Albrecht	+0.3
3.......	756 IV	1905, Aug. 3.697	– 0.9	Albrecht	+1.9
4.......	785 III	25.676	– 4.2	Albrecht	+1.1
5.......	935 II	1906, Oct. 7.571	{ + 3.3 + 2.1	Paddock Curtis	} –1.1
6.......	966 II	Nov. 6.514	{ + 0.4 + 1.5	Paddock Curtis	} –1.4
7.......	1292 III	1907, April 30.924	{ – 1.5 + 0.9	Paddock Curtis	} +0.7
8.......	1323 III	May 11.831	– 3.8	Curtis	–0.2
9.......	1336 IV	13.880	+ 4.5	Curtis	+0.1
10.......	1343 IV	14.886	+ 7.3	Curtis	–0.3
11.......	1349 II	18.835	+ 4.5	Curtis	+1.3
12.......	1382 II	June 22.884	+ 2.9	Curtis	–1.1
13.......	1400 IV	26.764	– 5.8	Curtis	–0.7
14.......	1407 II	July 1.886	+10.4	Curtis	+1.3
15.......	1411 IV	2.685	+ 8.7	Curtis	–0.3
16.......	1418 II	3.768	+ 7.3	Curtis	+0.5
17.......	1428 IV	6.804	– 2.4	Curtis	+1.2
18.......	1435 III	19.742	– 5.8	Curtis	–0.5
19.......	1441 IV	20.767	– 4.0	Curtis	+0.4
20.......	1445 II	25.645	+ 7.7	Curtis	–1.5
21.......	1451 I	27.778	+ 5.9	Curtis	+0.7
22.......	1456 II	29.630	– 2.6	Curtis	–1.1

The lines upon which the above radial velocities depend are the six characteristic lines of this type, no others being visible in this region of the spectrum.

λ 4267.316 *C*
4340.634 *H*
4388.100 *He*
4437.718 *He*
4471.646 *He*
4481.400 *Mg*

A set of preliminary elements was first derived graphically by the method of Lehmann-Filhés.[1] Changes were then made in the derived elements, after comparing with the curve given by the observations, and several sets of elements tested by the observation values. It is the opinion of the writer that the application of the method of least squares to stars of this type of spectrum and number of lines will not be warranted, except in the case that a large number of observations are available extending over a long interval of time. With some experience in the method it is possible in a relatively short time to test and change the elements given by the graphical solution until the resulting values would be little if any bettered by a least-square solution. The computation of even three or four test ephemerides involves much less labor and time than a least-square solution.

By such methods the following set of elements was decided upon as best satisfying the data furnished by the observed radial velocities:

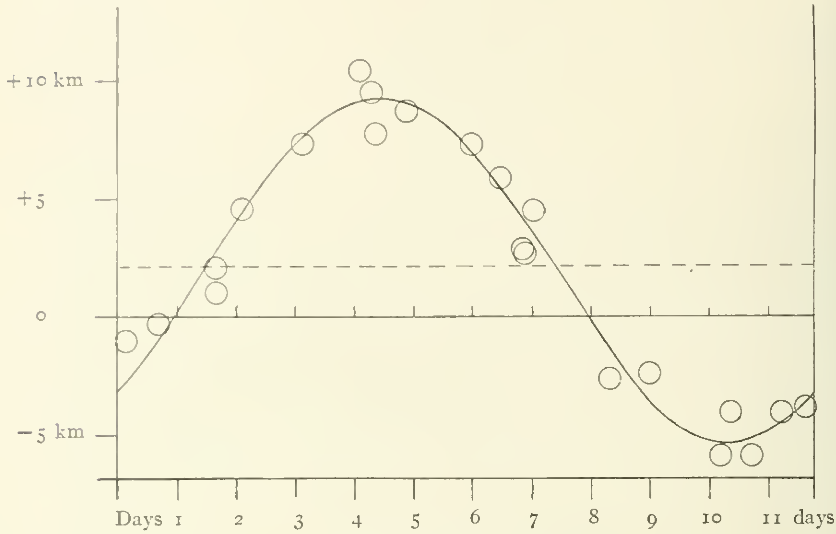
ELEMENTS OF α PAVONIS

Period = 11.753 days,
$e = 0.01$,
$K = 7.25$,
$T =$ J. D. 2416379.90,
$\omega = 224\overset{\circ}{.}80$.
Velocity of system = +2.0 km,
$a \sin i = 1{,}170{,}000$ km.

The total range in the radial velocity is only 14.5 kilometers. The observations are about as well satisfied by a circular orbit, as the eccentricity is evidently very small.

[1] *A. N.*, 136, 17, 1894.

This velocity-curve and the separate observations are plotted in the accompanying diagram, the dotted line, as usual, representing the velocity of the center of mass of the system. The numerical values



Velocity-Curve of *α Pavonis*

of the residuals secured by comparison of the observed radial velocities with an ephemeris computed from these elements is given in the final column of the observation table.

THE D. O. MILLS EXPEDITION
Santiago, Chile, August 1907

DEFINITIVE ORBIT OF THE SPECTROSCOPIC BINARY *ω DRACONIS*

By ARTHUR B. TURNER

The spectroscopic binary *ω Draconis* was discovered by Director Campbell and announced by him in the *Astrophysical Journal* in August 1899 (**10**,179). It is an *F*-type star with rather broad, fuzzy lines.

The orbit depends on the following twenty-six plates taken with the Mills Spectrograph, which have been measured and reduced by the writer:

No.	Date G. M. T.	Observed Velocity	O.−C. Preliminary Orbit	O.−C. Final Orbit	Comparison of Residuals
		km	km	km	km
1.......	1899, July 25.776	+19.2	+1.54	+0.62	+0.01
2.......	Aug. 8.779	−45.8	+0.25	+0.24	−0.06
3.......	9.774	−11.7	+0.21	−0.42	+0.03
4.......	29.721	−48.5	−0.08	+0.06	−0.04
5.......	1906, June 29.852	+11.8	+1.50	+1.16	−0.06
6.......	July 3.735	+10.6	−0.05	−0.22	−0.04
7.......	10.867	− 8.9	−2.03	−1.99	+0.05
8.......	11.851	−42.8	+0.30	+0.51	+0.06
9.......	15.731	+10.6	+1.58	+1.27	−0.04
10.......	16.722	−31.2	−0.82	−0.65	+0.03
11.......	22.720	−49.9	−1.55	−1.30	−0.01
12.......	23.798	−32.4	−0.92	−0.39	−0.01
13.......	25.799	+19.8	−0.84	−1.44	−0.05
14.......	26.807	−11.7	−0.55	−0.57	±0.00
15.......	29.767	− 3.8	−0.90	−0.66	+0.10
16.......	30.753	+21.6	−0.60	−1.20	−0.01
17.......	Aug. 1.786	−38.5	−0.40	−0.23	±0.00
18.......	6.765	−28.0	−0.47	−0.35	+0.01
19.......	7.759	−47.6	+1.74	+2.04	−0.02
20.......	9.759	+14.4	+1.71	+1.50	+0.07
21.......	13.768	−37.6	−0.97	−0.42	+0.01
22.......	16.713	− 3.5	−1.17	−1.35	−0.09
23.......	Sept. 6.712	+ 3.7	+1.29	+1.07	+0.05
24.......	1907, July 28.773	−14.2	+0.95	+1.51	+0.04
25.......	Aug. 5.771	−15.1	+0.63	+0.54	−0.01
26.......	7.751	−38.6	−0.92	−0.29	−0.02
	[*pvv*]		26.782	22.678	

By the method of Lehmann-Filhés[1] preliminary elements were obtained, but owing to the fact that the orbit was so nearly a circle,

[1] *Astronomische Nachrichten*, 136, 17, 1894.

some difficulty was encountered in getting satisfactory values for ω and T. The above preliminary residuals were obtained by diminishing ω by 270° and making a corresponding change in T and giving a small value to the eccentricity. The following are the

PRELIMINARY ELEMENTS

$$
\begin{aligned}
\text{Velocity of system} &= -13.65 \text{ km},\\
T &= 1906 \text{ July } 23.285,\\
&= \text{Julian Day } 2417385.285,\\
e &= 0.0058,\\
\omega &= 319^\circ\!.837,\\
\log \mu &= 0.07558,\\
\mu &= 68^\circ\!.1866,\\
K &= 35.80,\\
\text{Period} &= 5^d\!.27963,\\
a \sin i &= 2{,}599{,}000 \text{ km}.
\end{aligned}
$$

The differential coefficients were then computed from these elements and the equations of condition formed. The epoch, Julian Day 2416329.359, was used in computing the coefficients of $\delta\mu$. A sixth unknown with the coefficient unity was introduced to allow for change in the velocity of the system. The equations were then weighted and the coefficients made homogeneous by the use of the following factors:

$$
\begin{aligned}
x &= \delta V && = \delta V\\
y &= \frac{K\mu}{(1-e^2)^{\frac{3}{2}}}\delta T && = 42.61\ \delta T\\
z &= 1466.4\frac{K}{(1-e^2)^{\frac{3}{2}}}\delta\mu && = 52500\ \delta\mu\\
u &= \delta K && = \delta K\\
v &= K\delta\omega && = 35.80\ \delta\omega\\
w &= K\delta e && = 35.80\ \delta e\\
\log \text{unit error} &= 0.2405 && = 0.2405
\end{aligned}
$$

The following equations were then obtained:

							Wt.
$+1.000x$	$-0.498y$	$-0.498z$	$+0.875u$	$+0.496v$	$+0.948w$	$-0.885=0$	1
$+1.000$	-0.414	-0.411	-0.905	$+0.420$	$+0.013$	$-0.144=0$	1
$+1.000$	-1.008	-0.998	$+0.049$	$+1.003$	-0.705	$-0.121=0$	1
$+1.000$	-0.217	-0.212	-0.972	$+0.223$	$+0.416$	$+0.046=0$	1
$+1.000$	$+0.747$	-0.541	$+0.669$	-0.743	-0.730	$-0.862=0$	1
$+1.000$	-0.748	$+0.544$	$+0.678$	$+0.743$	$+0.571$	$+0.029=0$	1
$+0.707$	$+0.691$	-0.506	$+0.134$	-0.692	-0.667	$+0.825=0$	½
$+1.000$	$+0.562$	-0.408	-0.822	-0.559	$+0.880$	$-0.172=0$	1
$+1.000$	$+0.777$	-0.571	$+0.633$	-0.773	-0.790	$-0.908=0$	1
$+1.000$	$+0.872$	-0.642	-0.469	-0.877	$+0.114$	$+0.471=0$	1
$+1.000$	$+0.230$	-0.170	-0.969	-0.228	$+0.973$	$+0.891=0$	1
$+1.000$	-0.867	$+0.642$	-0.498	$+0.869$	-0.941	$+0.529=0$	1
$+1.000$	$+0.302$	-0.224	$+0.958$	-0.296	$+0.256$	$+0.483=0$	1
$+1.000$	$+0.992$	-0.737	$+0.071$	-0.994	-0.840	$+0.316=0$	1
$+1.000$	-0.966	$+0.719$	$+0.298$	$+0.960$	-0.271	$+0.517=0$	1
$+1.000$	-0.087	$+0.065$	$+1.000$	$+0.090$	$+0.864$	$+0.345=0$	1
$+1.000$	$+0.718$	-0.536	-0.683	-0.723	$+0.602$	$+0.230=0$	1
$+1.000$	$+0.911$	-0.683	-0.389	-0.916	-0.060	$+0.270=0$	1
$+1.000$	-0.003	$+0.003$	-0.996	$+0.007$	$+0.760$	$-1.000=0$	1
$+1.000$	-0.690	$+0.521$	$+0.735$	$+0.686$	$+0.696$	$-0.983=0$	1
$+1.000$	-0.762	$+0.576$	-0.643	$+0.766$	-0.760	$+0.557=0$	1
$+0.707$	$+0.667$	-0.507	$+0.223$	-0.669	-0.703	$+0.475=0$	½
$+1.000$	$+0.894$	-0.690	$+0.448$	-0.892	-0.975	$-0.741=0$	1
$+0.707$	-0.712	$+0.707$	-0.030	$+0.709$	-0.583	$-0.386=0$	½
$+1.000$	$+0.990$	-0.989	-0.059	-0.994	-0.674	$-0.362=0$	1
$+1.000$	-0.737	$+0.737$	-0.672	$+0.741$	-0.708	$+0.529=0$	1

These gave the following normal equations:

$24.499x$	$+1.455y$	$-4.719z$	$-1.432u$	$-1.452v$	$-1.742w$	$-0.319=0$
	$+13.255$	-7.804	$+0.149$	-13.254	-1.437	$-0.350=0$
		$+8.874$	-0.074	$+7.810$	$+1.261$	$+1.447=0$
			$+11.221$	-0.163	-0.799	$-2.833=0$
				$+13.255$	$+1.438$	$+0.345=0$
					$+12.453$	$-0.898=0$

The solution supplied the following corrections to the elements:

$$\delta V = -0.0316 \text{ km},$$

$$\delta T = +0.198 \text{ days},$$

$$\delta\mu = -0.0000107 \text{ radians},$$

$$= -0^\circ.0006,$$

$$\delta K = +0.459,$$

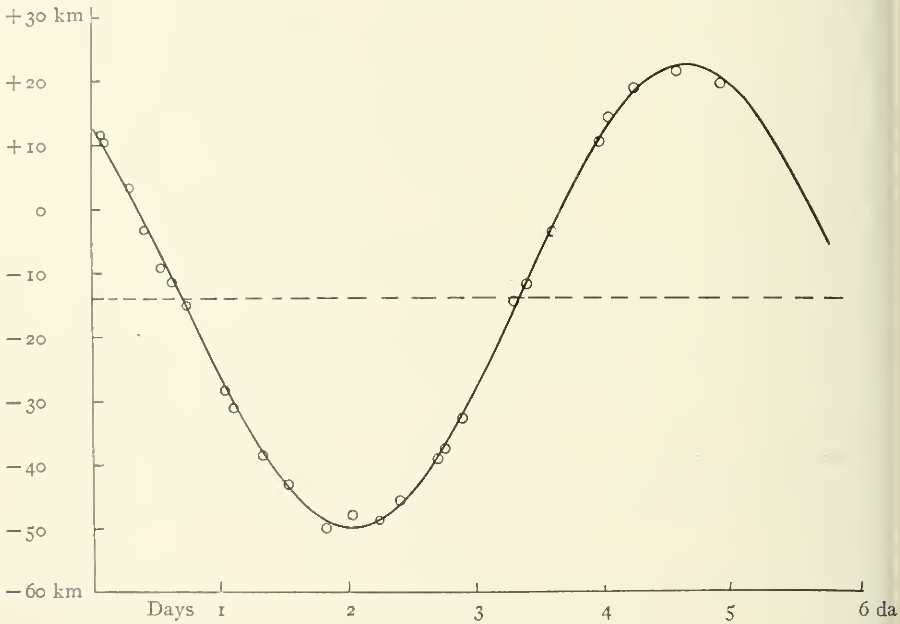
$$\delta\omega = +0.243 \text{ radians},$$

$$= +13^\circ.924,$$

$$\delta e = +0.00491.$$

The probable error of a single observation is ±0.75 kilometer per second. The final elements, with their probable errors, are as follows:

$$\begin{aligned}
\text{Velocity of System} &= -13.68 \pm 0.16 \text{ km},\\
T &= 1906 \text{ July } 23.493 \pm 0.394 \text{ days},\\
&\quad \text{Julian Day } 2417385.493,\\
e &= 0.0107 \pm 0.0060,\\
\omega &= 333^\circ\!.761 \pm 26^\circ\!.9,\\
\log \mu &= 0.0755725 \pm 0.0000027,\\
\mu &= 68^\circ\!.1860 \pm 0^\circ\!.0004,\\
K &= 36.26 \pm 0.24,\\
\text{Period} &= 5.27968 \pm 0.00003 \text{ days},\\
a \sin i &= 2,632,300 \text{ km}.
\end{aligned}$$



Velocity-Curve of *ω Draconis*

The comparison of the residuals obtained from the final elements with those obtained from substitution in the equations of condition is shown in column six of the table. The small differences indicate that a second solution is unnecessary.

The final velocity-curve is represented by the accompanying diagram, the observed places as given by the plates being represented by small circles. The velocity of the center of mass of the system is represented by the dotted line.

In conclusion I wish to thank Director Campbell for putting at my disposal the necessary facilities of the Observatory for carrying on the above investigation.

Mount Hamilton
August 31, 1907

THE SPECTROSCOPIC BINARY η *VIRGINIS*

By NAOZO ICHINOHE

The variability of the radial velocity of this star was discovered at this observatory and also independently at the Lick Observatory. The investigation of its orbit was undertaken by me two years ago at the suggestion of Mr. Frost, to whom my sincere thanks are due; and the material has now become tolerably sufficient for the discussion of the principal star. The number of spectroscopic binaries is small in which the fainter component is strong enough to give a well measurable spectrum; and the velocity-curve for the faint component has been published in hardly any instance. As Messrs. Frost and Adams have pointed out, η *Virginis* shows a pretty intense spectrum of the faint component on the three-prism spectrograms. As the number of lines which are well measurable is comparatively large, the resulting velocity for the component is pretty accurate. This is why I feel so interested to investigate this star, but the number of plates taken with the full dispersion of the Bruce spectrograph is not sufficient for the satisfactory discussion of the faint component; some plates were taken with the single prism, but on such plates I was not able to see the lines of the spectrum of the faint component.

The whole number of the spectrograms so far obtained at this observatory is 25, among which 16 plates were taken with the three-prism spectrograph and the remaining 9 plates with the single prism. The following journal of observations of η *Virginis* is similar to those for which I have already determined the spectroscopic orbits. It is to be noticed that the column of temperature is slightly different from others in that in the cases of the single-prism spectrograms, the temperature inside the outer case of the spectrograph is given, but in the cases of the three-prism plates, the reading of the thermometer inserted in the inner case is recorded.

Among the plates, on IB 1041 the comparison spectrum was too weak and the two last named are very weak and not suitable for accurate measurement.

Plate	Date	G. M. T.	Exposure	Slit-Widths mm	Temp.	Observer	Seeing
B 487....	1903, Jan. 14	23^h 17^m	95^m	0.046	− 6°3 C.	A	3; 2
A 388....	1903, Jan. 16	22 14	132	0.046	− 0.3	A	3; 3
B 493....	1903, Feb. 4	23 12	120	0.046	− 4.9	F	3; 2
A 399....	1903, Feb. 5	20 47	108	0.046	− 6.1	A	3; 3
B 539....	1903, Dec. 13	22 46	120	0.051	−18.3	F	4; 2
B 551....	1904, Feb. 19	21 11	108	0.036	− 7.6	F	4; 4
IB 488....	1905, Jan. 21	21 12	45	0.038	− 9.9	B	3; 2
B 580....	1905, Feb. 27	19 47	120	0.044	+ 0.2	FB	3; 2
B 626....	1906, Jan. 5	21 33	124	0.046	− 2.4	B	3; 3
B 650....	1906, Mar. 16	21 59	120	0.051	− 7.8	F	3; 3
B 651....	1906, Mar. 19	18 54	180	0.051	− 3.9	F	2; 2
B 657....	1906, April 16	19 28	120	0.059	+11.0	B	4; 3
IB 742....	1906, April 23	16 35	46	0.051	+ 9.7	F	3; 3
B 664....	1906, May 18	16 45	120	0.046	+22.8	B	4; 2
IB 926....	1906, Dec. 14	22 12	53	0.051	+ 0.8	B	3; 2
B 685....	1906, Dec. 23	23 07	130	0.057	− 7.3	Fox	4; 3
B 700....	1906, Dec. 28	21 08	135	0.057	+ 1.7	B	2; 2
IB 950....	1907, Jan. 21	22 53	46	0.051	−10.4	F	2; 2
IB 962....	1907, Jan. 25	23 10	45	0.051	−14.4	B	3; 3
IB 989....	1907, Feb. 18	21 12	44	0.051	+ 2.4	B	3; 3
IB1001....	1907, Feb. 22	22 00	45	0.051	− 9.0	B	3; 3
IB1013....	1907, April 1	14 52	48	0.046	+ 1.4	B	2; 3
IB1041....	1907, April 26	17 26	63	0.051	+ 3.6	F	3; 3
B 717....	1907, June 14	15 28	120	0.040	+22.5	F	3; 3
B 720....	1907, June 16	15 12	120	0.051	+26.7	B	2; 3

The examination of the plates shows that the star belongs to the later stage of the *Orion* type, or more properly to the first stage of the *Sirian* type. The lines are very narrow and well defined, so that they are very well measurable. The general character of the spectrum of the star may be stated as follows. The hydrogen lines become exceedingly narrow and intense, and many metallic lines are very well developed, especially those of iron and titanium. The helium lines do not appear, or they are very weak. The magnesium line λ 4481 is as strong as $H\gamma$. The silicon lines $\lambda\lambda$ 4128 and 4131 are well seen, but I could not see other lines belonging to the same element. The spectrum of the faint component is an exact duplicate of that of the bright component. This might show that both components must have a very close relation to each other; probably they have a common origin and constitute a system.

The measurement of the plate A 388 was made by Mr. Adams; plate B 493 was measured by both Messrs. Frost and Adams, and the measurement of A 399 was again made by Mr. Adams alone. These

results can be seen in their announcement of the discovery.[1] The results of two plates by the Lick observers can be found in the same journal.[2] I have measured all the remaining plates obtained here of the star. The following table contains the results of the measurements. As usual, the first column gives the plate numbers; the second the epochs of the observations in Julian days, two decimal places being retained. The third gives the measured velocities reduced to the sun. The fourth column shows the number of lines which I have measured for the determination of the velocity on each plate. The results for the plates B 717 and B 720 will be considered only as the approximate values, and I have omitted them from the discussion except in the case of the faint component.

η Virginis

Plate No.	Julian Day	v	n	Phase	v_c	$v-v_c$
B 487......	2416129.97	−27.6	9	0.0	−27.8	+0.2
A 388......	6131.92	−31.5	14	1.9	−31.4	−0.1
B 493......	6150.97	+ 0.4	16	21.0	+ 1.1	− 0.7
A 399......	6151.87	+ 3.4	16	21.9	+ 3.0	+0.4
B 539......	6462.95	+19.0	14	45.4	+18.9	+0.1
B 551......	6530.88	+19.9	13	41.4	+19.6	+0.3
IB 488......	6867.88	− 0.5	7	18.9	− 2.2	+1.7
B 580......	6904.83	+ 5.4	12	55.9	+10.4	−5.9
B 626......	7216.90	−30.2	14	8.4	−30.8	+0.6
B 650......	7286.92	−33.7	15	6.6	−33.4	−0.3
B 651......	7289.79	−27.0	16	9.4	−28.9	+1.9
B 657......	7317.81	+18.9	12	37.4	+19.1	−0.2
IB 742......	7324.69	+22.4	13	44.3	+19.3	+3.1
B 664......	7349.70	−24.2	14	69.3	−21.1	−3.1
IB 926......	7559.92	− 0.6	13	63.9	− 5.4	+4.8
B 685......	7568.96	−29.5	16	1.0	−29.6	+0.1
B 700......	7573.88	−32.1	14	5.9	−33.8	+1.7
IB 950......	7597.91	+20.0	15	30.0	+14.7	+5.3
IB 962......	7601.97	+20.3	9	34.0	+17.7	+2.6
IB 989......	7625.88	+10.3	18	57.9	+ 7.6	+2.7
IB 1001......	7629.92	+ 1.3	17	62.0	− 0.8	+2.1
IB 1013......	7667.62	+12.6	6	27.8	+12.4	+0.2
IB 1041......	7692.72	+ 7.2	9	52.9	+14.2	−7.0
B 717......	7741.65	+21.7	7	29.9	+14.8	.....
B 720......	7743.63	+26.4	7	32.9	+17.1	.....

The lines and their normal wave-lengths which are used for the star are as follows. In the table, the last column shows how many times the corresponding line has been used for the star, the whole number of the plates being 25.

[1] *Astrophysical Journal*, **17**, 150, 1903. [2] *Ibid.*, **18**, 307, 1903.

Element	λ	n	Element	λ	n
Ca, K	3933.825	4	—	4385.548	3
Fe	3936.965	1	*Ti*	4387.007	1
Fe	4005.408	2	*Ti*	4395.201	12
Ti	4012.541	2	*Ti−Cr*	4399.935	3
Ti	4024.726	1	*Fe*	4404.927	5
Ti	4028.497	2	*Cr*	4411.240	1
Fe−Ti	4030.646	1	—	4416.985	2
Fe	4045.975	8	*Ti*	4417.884	1
Fe−Ti	4053.981	1	*Ti+Fe*	4427.420	1
Fe	4063.759	5	*Ti*	4443.976	18
Fe	4065.537	1	*Ti*	4468.663	19
Fe+Fe	4067.248	1	*Fe*	4472.884	1
Fe	4071.908	3	*Mg*	4481.400	25
Sr	4077.885	3	*Ti*	4488.493	1
Ti	4078.631	1	*Ti*	4489.262	1
Hδ	4101.890	1	—	4491.570	2
Si	4128.211	1	*Ti*	4501.445	19
Si	4131.047	1	*Fe?*	4508.455	12
Fe	4132.235	1	—	4515.508	5
Ti; Cr−	4163.818	3	*Fe?*	4520.397	10
—	4171.854	1	—	4522.802	11
Fe	4173.480	1	*Fe*	4528.798	1
Fe	4202.198	2	*Ti?*	4529.656	1
Fe	4215.581	2	*Ti*	4534.139	12
Mn−Fe	4233.328	1	*Cr*	4541.690	3
Fe	4271.934	1	*Fe+Ti*	4549.767	22
Fe	4294.301	1	*Ba*	4554.211	8
Ti	4302.085	1	—	4556.063	4
Fe	4308.081	2	*Cr?*	4558.827	5
Ti	4313.034	1	*Ti*	4563.939	10
Ti	4315.138	1	*Co−Fe*	4565.842	1
Ti	4325.939	3	*Ti*	4572.156	10
Hγ	4340.634	8	*Fe*	4584.018	4
Cr	4351.930	4	—	4588.381	1
Ti	4367.839	1	*Ti*	4590.126	1
Fe	4383.720	6	*Ti*	4629.521	1

The investigation of the period of the oscillation was made by myself in the spring of 1906. At that time the material was small, but after numerous trials, I found a value of $71^{d}.9$ for the period. For this determination, the two Lick plates were of great service. The value satisfied all the results known at that time very well. The results obtained later do not change this value, so $71^{d}9$ was taken as the period for the present discussion.

Let us first consider the principal component. At the beginning the plates were taken with the full dispersion and the preliminary velocity-curve was drawn with all the data known. The curve and the observations were accordant. The two Lick plates were also accordant. But when the plates began to be taken with the single-

prism spectrograph, it became necessary to change the nature of the curve if we assume that there is no systematic difference between both series of observations made with the three-prism and single-prism spectrograph. And if we do so, the result is that the three-prism results lose their good accordance, especially the plate B 580, and the residuals become larger than when we take the curve depending merely upon those results. I already suspected such systematic error in the measures of μ *Sagittarii*, but unfortunately the question is not settled. If there exists some difference of this nature, we cannot use both series of observations without the danger of introducing some errors in the computed elements of the orbit, unless we know the nature of the systematic difference and apply the proper corrections to the observations. If we had sufficient material to discuss the star independently for both series, it would be interesting, but we have not the data needed. Thus I was obliged to assume that we can use both kinds of observations equally well, notwithstanding that I suspect some differences.

Now, the fifth column of the above table was calculated with the period $71\overset{d}{.}9$ and assuming 0^d0 phase for the epoch J. D. $2416129\overset{d}{.}97$. Then, as usual, the column v was taken for the ordinates and the column Phase for the abscissas. All the observations being platted in this way, a smooth curve was drawn through or near to these points. The curve enabled me to determine the radial velocity of the center of gravity of η *Virginis* as follows:

Radial velocity of the center of gravity $= -0.4$ km.

Thus we can say that the center of gravity of this stellar system is at rest referred to the sun.

The examination of the curve gave then the following values for calculating the elements according to the method of Lehmann-Filhés:

$$A = 20.0 \text{ km}, \qquad B = 33.6 \text{ km},$$
$$z_1 = 738, \qquad z_2 = -738,$$
$$t_1 = 61\overset{d}{.}9, \qquad t_2 = 92\overset{d}{.}0.$$

We now compute the following elements:

$$U = 71\overset{d}{.}9,$$
$$u_1 = 75^\circ\ 18',$$

$$\omega = 180^\circ\ 0',$$
$$e = 0.254,$$
$$\mu = 5^\circ\!.01,$$
$$\text{or } \log \mu = 8.9414,$$
$$T = 76^{d}\!.96,$$
$$\text{or } T = J.D.\ 2416206.93,$$
$$a \sin i = 25{,}290{,}000 \text{ km}.$$
$$m + m' = \frac{0.13\ \odot}{\sin^3 i}\ .$$

If the inclination be not quite small, a as well as $m+m'$ will assume the following values in astronomical units.

i	a	$m+m'$
30°	0.3402	1.02
45°	0.2406	0.36
60°	0.1950	0.19
75°	0.1761	0.14
90°	0.1701	0.13

To see how the set of elements will represent the observations I have computed an ephemeris using these elements. The sixth column of the above table shows these computed values, and in the last column, the differences between the observed and computed values, $v-v_c$, are given. We see that the elements represent the observations pretty well, but for the plates B 580 and B 664 we have the residuals -5.0 and -3.1 km respectively. These are comparatively great for the results obtained with the three-prism spectrograph. Mr. Campbell did not give the times of his observations, so that we cannot obtain exact phases for them, but when we assume that he observed the star on the meridian, then the residuals will be $+1.2$ and -3.2 km respectively. In Fig. 1 the curve is drawn with the computed values, and the single circles show the values as observed with the one-prism arrangement of the spectrograph; the double circles show the values observed with three prisms; the Lick results are represented by the circles with black centers.

Let us next examine the faint component of η *Virginis.* The results of the observations of the component are shown in the follow-

ing table. In the column under the head of phase we assumed the same value of the period as for the other component.

η Virginis (Second Component)

Plate	v	n	Phase	v_c	$v-v_c$
B 487	+39 km	8	0.0	+58 km	−19 km
A 388	+42	4	1.9	+59	−17
B 493	+62	6	21.0	+39	+23
B 539	− 8	7	45.4	− 2	− 6
B 551	−29	12	41.4	− 5	−24
B 580	+67	12	55.9	+26	+41
B 626	+41	12	8.4	+58	−18
B 650	+41	15	6.6	+60	−19
B 651	+43	16	9.4	+58	−15
B 657	−36	12	37.4	− 4	−32
B 664	+36	12	69.3	+55	−19
B 685	+47	10	1.0	+58	−11
B 700	+45	10	5.9	+60	−15
B 717	−41	6	29.9	+ 6	−35
B 720	−34	7	32.9	+ 1	−33

These are platted in Fig. 2, which shows that the velocity of the faint component varies with the same period $71^{d}.9$; but the nature

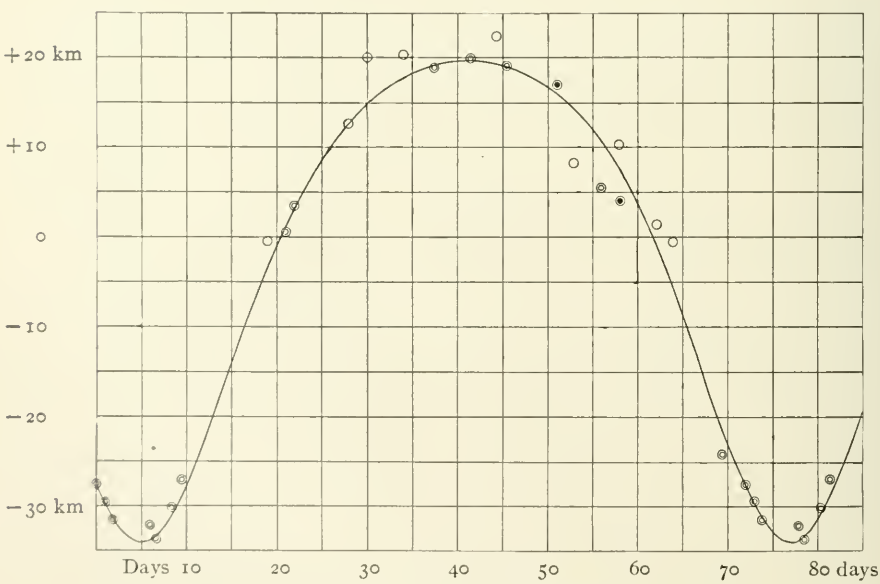


Fig. 1.—Velocity-Curve of η Virginis, Brighter Component

of the curve is not simple as the other component. Although we have not sufficient observations for this component, still it would probably be safe to draw the velocity-curve as shown in the figure. The curve permits the two following conclusions at once: (1) the radial velocity of the center of gravity of the faint component does not coincide with that of the principal one; and (2) the curve is not simply periodic with the value 71^d9 but it is affected by another cause whose

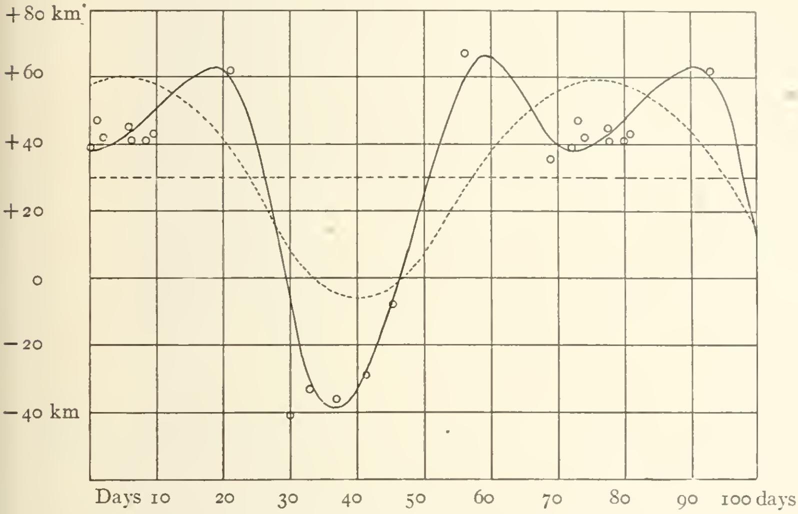


FIG. 2.—Velocity-Curve for Second Component of η Virginis

action is also periodic commensurably with the main period. From these results, I think the faint component is not only a companion to the principal star but that there is at least another component nearer to the principal than the faint component.

To discuss these points more fully, I first determined the radial velocity of the center of gravity of this component and the result is +30 km. This indicates that the faint component is receding from the bright component with a velocity of about 2,166,000 km in a day in the line of sight. If this continues for quite a long time, these two components cannot remain a mechanical system. But our observations cover only a little more than four years so that we cannot conclude anything as to this. Still, we may suppose that the faint

component is situated very far from the bright one and revolves around the central sun with a long period so that the radial velocity obtained for the center of gravity is simply the projection of the orbital velocity in the line of sight. Then, the oscillation of the radial velocity of the component may be looked upon as a perturbation by the principal component or its nearer companion. If such supposition be correct after a longer series of observations of this faint

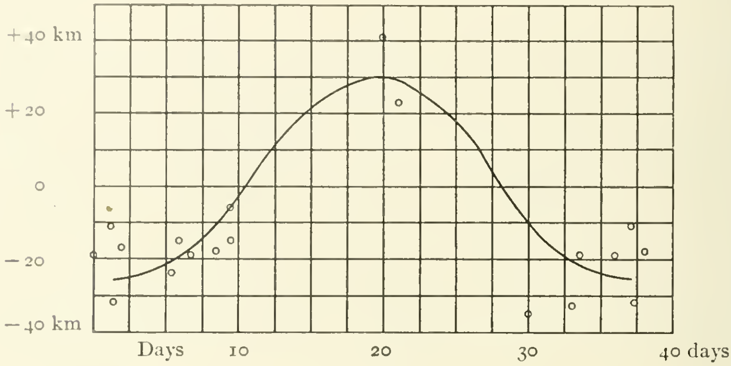


FIG. 3

component, covering many decades, it would be possible to know more precisely about the system of *η Virginis*.

To get a better conception of the perturbation, I have drawn a mean curve, Fig. 3, balancing the smaller disturbances in such way that the areas inclosed, above and below, by both the curve and the observed curve become equal, and they cancel out when we assign a + sign for the area above and a − sign for that below. The curve is dotted in the figure. Now finding the residuals, the observed values minus the computed, we have the fifth column of the last table. Finally, examining these we see that the residuals have a period of $35^{d}.95$, or exactly one-half of the main period $71^{d}.9$. The third figure shows the curve drawn with the residuals as the ordinates and the phases as abscissas. Such irregularity was found in the cases of *ζ Geminorum*, *W Sagittarii* and also other short-period variables. We do not know yet what is the real cause of this oscillation. Mr. Roberts gave an explanation of such disturbance and found that when we are concerned with bodies whose dimensions are comparable with that of the

distance between the centers of the components, we must expect such periodic oscillation in the cases where the bodies are not spherical. The above are simply inferences which we can reach at present, but of course the true nature of the mystery remains without a proper explanation.

YERKES OBSERVATORY
August 1907

EIGHT STARS WHOSE RADIAL VELOCITIES VARY

By W. W. CAMPBELL AND J. H. MOORE

The following six stars have been shown to have variable radial velocities. The plates of dates earlier than June 1903 were taken with the Mills spectrograph for which minimum deviation was set at $H\gamma$, while plates of later dates were obtained with the remounted Mills spectrograph whose minimum deviation is set at λ 4500. The observations are not distributed in such a way as to give a definite idea of the period of any of these binary systems.

1 o Tauri ($\alpha = 3^h\ 19^m.4$; $\delta = +8^\circ\ 40'$)

Plate	Date	Velocity	Measured by
965 C................	1898, September 23	−17 km	Campbell
		−18.7	Burns
974 B................	1898, September 28	−16	Campbell
		−16.9	Burns
1449 D................	1899, September 6	−18	Campbell
		−21.7	Burns
3841 F................	1904, October 4	−25	Moore
		−23.7	Newkirk
4052 A................	1905, October 9	−22	Moore
		−20.8	Newkirk
4428 E................	1906, September 16	−20	Moore
		−19.2	Newkirk
4837 D................	1907, August 2	−15	Moore

The spectrum of this star is of the *K* type. Its variable radial velocity was suspected by Mr. Moore in 1904 and confirmed by the measures of recent plates. The period is probably long.

5 f Tauri ($\alpha = 3^h\ 25^m.4$; $\delta = +12^\circ\ 35'$)

Plate	Date	Velocity	Measured by
517 A................	1897, October 19	+15.2 km	Wright
		+14	Campbell
531 C................	1897, October 28	+14.9	Burns
		+12	Reese
998 A................	1898, October 10	+10.7	Burns
		+11	Campbell
1010 D................	1898, October 17	+12.2	Burns
		+11	Campbell
1022 C................	1898, October 19	+11.6	Burns
3051 E................	1903, November 29	+ 9	Curtis
3530 D................	1904, November 7	+22	Moore
4843 D................	1907, August 5	+27	Moore

The type of spectrum is *K*. The period of this binary is probably long. Its variable velocity was discovered by Mr. Moore.

7 Camelopardalis ($\alpha = 4^h\ 49^m.3$; $\delta = +53°\ 35'$)

Plate	Date	Velocity	Measured by
2584 A	1902, November 4	−40 km	Burns
		−33	Curtis
		−20	Curtis
3072 E	1903, December 6	−17	Moore
4612 B	1907, February 7	+20.5	Moore
4643 D	1907, February 27	− 3.2	Moore
4647 B	1907, March 13	− 1.8	Moore
4683 A	1907, April 22	+22.5	Campbell
4861 D	1907, August 8	+23	Moore

The spectrum is of type *A*. The magnesium line λ 4481 is good on all of the plates and on some of them the iron line λ 4549 is also measurable. The binary character of this star was shown by Mr. Moore from a measure of the third plate, and is confirmed by measures of later plates. Its period is undoubtedly short.

A *Bootis* ($\alpha = 14^h\ 13^m.8$; $\delta = +35°\ 58'$)

Plate	Date	Velocity	Measured by
4234 B	1906, May 31	−40 km	Moore
		−38.9	Newkirk
4631 D	1907, February 10	−12	Moore
4656 A	1907, March 29	− 8	Moore
4680 C	1907, April 21	−11	Campbell
4730 B	1907, May 29	−18.6	Campbell

The type of spectrum is *I*. The first, fourth, and fifth plates are underexposed. However, many of the lines are easily measurable on these plates, so that there is no doubt but that the variation is real. The period is probably short. The variable velocity was discovered by Mr. Moore from the second plate.

β Coronae ($\alpha = 15^h\ 23^m.7$; $\delta = +29°\ 27'$).

Plate	Date	Velocity	Measured by
1717 D	1900, April 18	−15 km	Wright
		−17.7	Burns
1728 B	1900, May 13	−16	Wright
		−18.0	Burns
2121 F	1901, May 6	−20	Reese
		−18.0	Burns
2339 D	1902, February 13	−17	Reese
		−15.0	Burns
3775 D	1905, April 11	−23.5	Moore
4655 E	1907, March 29	−33	Moore
4661 D	1907, April 8	−30	Moore
4804 A	1907, July 17	−28	Moore

The spectrum of this star is a very good *F* type.

The binary character was discovered by Mr. Moore. The period is probably long.

62 ξ Cygni ($\alpha = 21^h\ 1^m.3$; $\delta = +43°\ 32'$)

Plate	Date	Velocity	Measured by
3347 D	1904, July 19	−19.6 km	Newkirk
3522 A	1904, October 31	−19	Campbell
		−18.1	Newkirk
4830 B	1907, July 29	−24	Campbell
		−24.1	Newkirk
4870 A	1907, August 12	−22	Moore
		−22.7	Newkirk
4933 A	1907, September 15	−14	Moore

The spectrum is of type *K*, with very good lines. The variation is small, but the spectrum admits of accurate measurement, and there can be no doubt that the variation is a real one. The variable velocity of this star was discovered by Mr. Campbell. Its period is probably long.

Since the above list of spectroscopic binaries went to press, the following two stars have been shown to have variable velocities in the line of sight.

d Tauri ($\alpha = 4^h\ 30^m.2;\ \delta = +9°\ 57'$)

Plate	Date	Velocity	Measured by
4121 A................	1905, November 18	+ 52.2 km	Moore
4475 C................	1906, October 1	+102.0	Moore
4896 F................	1907, August 25	+ 66.5	Moore
4972 E................	1907, October 6	− 33.5	Moore
4995 E................	1907, October 13	− 45.2	Moore

The spectrum is a fair *F* type with rather broad but easily measurable lines. The variation in velocity was discovered by Mr. Moore. Its period is probably short.

ζ Cephei ($\alpha = 22^h\ 7^m.4;\ \delta = 57°\ 43'$)

Plate	Date	Velocity	Measured by
830 C................	1898, July 20	−18 km	Campbell
842 B................	1898, July 25	−17.4	Burns
1053 B................	1898, November 1	−18.5	Burns
1089 B................	1898, November 14	−18 −18.6	Campbell Burns
2209 D................	1901, July 31	−21 −21.2	Reese Burns
4402 B................	1906, September 2	−20 −19	Campbell Moore
4803 D................	1907, July 16	−14	Moore
4986 E................	1907, October 10	−16	Moore

The type of spectrum is *K*. The variable velocity was shown by Mr. Moore from the measures of recent plates.

LICK OBSERVATORY
August 20, 1907
October 23, 1907

TWO STARS WHOSE RADIAL VELOCITIES ARE VARIABLE

By W. H. WRIGHT

Spectrograms secured by the D. O. Mills Expedition to the Southern Hemisphere show the radial velocities of the following stars to be variable.

x Carinae ($\alpha = 11^h\ 4^m.4$, $\delta = -58°\ 26'$)

Date	Velocity	Measured by
1904, January 5..........	+17.1 km	R. H. Curtiss
1904, April 16............	+14.5	Wright
1905, January 6..........	+ 8.9	Wright
1905, February 24........	+ 7.4	Wright
1905, June 21............	+15.6	Wright
1906, February 24........	+17.4	Wright
1907, March 5...........	+ 4.5	Paddock
1907, April 27............	+ 3.3	Paddock
1907, May 13............	+ 3.7	Paddock

The lines in the spectrum of this star are somewhat diffuse and difficult of measurement. The variation was strongly suspected from the first six observations, and is amply confirmed by Mr. Paddock's measures of plates kindly secured by Professor H. D. Curtis.

ι Gruis ($\alpha = 23^h\ 4.7^m$, $\delta = -45°\ 47'$)

Date	Velocity	Measured by
1903, November 9........	−10.0 km	Wright
	− 9.7	Albrecht
1904, September 12.......	− 5	Palmer
	− 2.3	Wright
1904, October 27.........	− 4	Palmer
	− 5.6	Wright
1905, November 1........	− 3.8	Albrecht
	− 3.6	Wright
1905, November 13.......	− 3.8	Palmer
1905, November 19.......	− 3.0	Albrecht
1907, June 23............	−18.8	H. D. Curtis

The last observation, by Dr. Curtis, confirms the variation suspected from the preceding measures.

Mt. Hamilton
September 19, 1907

NOTE ON THE CAUSE OF THE PRESSURE-SHIFT OF SPECTRUM LINES

By W. J. HUMPHREYS

It was long ago suggested by Fitzgerald[1] that the increase in the specific inductive capacity of a gas, due to an increase in its density, is a *vera causa* for at least a part of the pressure-shift of spectrum lines; and very recently Larmor[2] made the same claim and showed that "if the vibrator operates as a simple Hertzian doublet," then, under certain reasonable assumptions, "the dielectric influence of the neighboring molecules is a *vera causa* of the right order of magnitude."

This theory is very pretty and I trust it will be worked up more completely, because if true it must provide for all the pressure effects, while a failure to do so will tend to prove that the vibrator is not of the nature of the simple Hertzian oscillator.

It appears safe to assume that the period of any vibrating body is dependent upon the elasticity both of the body itself and of the surrounding medium that takes up its vibrations, and therefore a change in either of these elasticities will change the period. In all such cases, if the inertia remains constant, we have the equation $et^2=k$, a constant, where e is the elasticity, and t the period. Therefore in the case of the vibrator that produces a spectrum line, any decrease in e causes a corresponding increase in λ^2. Besides, the greater λ, the less its increase necessary to produce a given increase in its square.

Consequently if the source of a spectrum line is a kind of Hertzian doublet, and its pressure-shift due to increase in the specific inductive capacity of the surrounding medium, it appears that in general we should expect among other results due to pressure:

a) A shifting of the entire line to the red.

What we get by experiment is a broadening of the line, both to the violet and to the red, with the latter predominating.

b) The increase of λ^2 to be a linear function of the pressure.

Unfortunately the change in λ is too small to test this relation.

[1] *Astrophysical Journal*, 5, 210, March 1897.

[2] *Ibid*, 26, 120, September 1907.

Let $\lambda_1 - \lambda_0$, or $\Delta\lambda$, be the change in wave-length produced by a change in pressure from p_0 to p_1, then

$\lambda_1^2 - \lambda_0^2 = 2\lambda_0\Delta\lambda + (\Delta\lambda)^2$, or simply $2\lambda_0\Delta\lambda$ to within the limits of experimental error, since $\Delta\lambda$ is always very small.

But $\Delta\lambda$ is approximately a linear function of the increase in pressure, and therefore so also is $2\lambda_0\Delta\lambda$, or $\lambda_1^2 - \lambda_0^2$ since $(\Delta\lambda)^2$ is negligible in comparison with the other term.

c) The greater the inductive capacity of the gas used, the greater the shift for any given pressure.

This conclusion is not yet established; it demands a knowledge, difficult to obtain, of the inductive capacity of the interior of the arc itself.

d) That the greater λ the less its shift.

Experiment does not give any well-marked relation between wave-length and pressure-shift, but the trend undoubtedly is in the other direction; that is, for the shifts to be greater in the case of lines of longer wave-length.

Possibly these and all other objections can be met by properly distributing, between the interior of the atom itself and its surrounding medium, the elasticity that determines the period of any given line. But this makes the problem a very complex one, and it seems doubtful whether it can ever be made to fit the facts of experiment as well as do magnetically interacting Saturnian atoms.

I fully agree with Larmor that the shift of spectrum lines probably is not strictly a pressure-effect, though it increases directly with the pressure of the surrounding gas. But I cannot at present agree with him in calling it a density-effect, since this would ascribe to heavy atoms an influence directly proportional to their mass, a result by no means experimentally established—in fact the masses of the neighboring atoms seem to be of secondary importance. Possibly the term proximity-effect might better suit the facts of experiment, as this refers to compactness of numbers without regard to their individual masses, and therefore while proportional to pressure is different from density.

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STUDIES IN SENSITOMETRY. II

ORTHOCHROMATISM BY BATHING

By ROBERT JAMES WALLACE

OBJECT

In a previous paper[1] the writer has referred to the evaluation of color-sensitiveness in photographic plates and has suggested a method for the production of spectrum negatives directly comparable with one another. This second paper deals further with this subject.

The main object of the present work was the investigation of orthochromatic action by bathing-methods, and the means of producing maximum effect throughout the entire visible spectrum with the dyes now at the disposal of the worker in photography. Not only was it desired that the plate be "panchromatic," but it was also sought to be as truly *iso*chromatic as possible; that is to say, equality of deposit for the various regions throughout the spectrum was considered as of primary importance, provided that it was not obtained at too great a sacrifice of speed. This latter consideration therefore eliminates the introduction of any dyestuff whose function would simply be a screening action upon the plate.

Throughout the course of the work certain combinations presenting more than common interest were noted and investigated as they occurred. In no case was any effort made to record a sensitiveness

[1] *Astrophysical Journal*, 25, 116, 1907.

which required an abnormal exposure when compared with that necessary to obtain full printing density in the blue-violet.[1]

METHOD OF WORK

The sensitizing influence of the cyanins and isocyanins upon gelatin dry plates has been the subject of investigation by a very large number of workers, principal among whom may be mentioned Eder and Valenta, von Hubl, Stenger, König, Mees and Sheppard, etc., and considerable has already been published. The work, however, does not appear to have been sufficiently extended, and it has therefore seemed good to the writer that with a chosen set of dyestuffs all possible combinations should be experimented upon and under variations sufficiently great to render the work comprehensive.

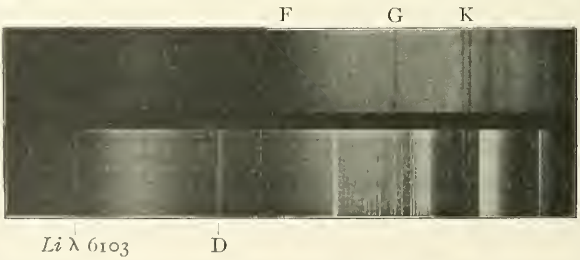
The dyes selected were assigned numbers and divided into groups, the first of which was arranged as follows:

1. Pinacyanol,
2. Pinaverdol,
3. Pinachrom,
4. Homocol,
5. Dicyanin.

With these five numbers as a base the following combinations were made:

1, 12, 13, 14, 15, 123, 124, 125, 134, 135, 145, 1234, 1345, 1235, 1245, 12345,

[1] A note may be interpolated here upon the fallacious results obtained with bright-line, discontinuous spectra in the estimation of chromatic sensitiveness. It is possibly as true as it is practical that if a plate can be impressed with a radiation of certain wave-length, it is then "sensitive to" such radiation; but it is well known that plates may be



"forced" in exposure, or (what amounts to the same thing) the intensity of the radiation may be so increased that a sensitiveness is recorded in a region to which the plate is, in the narrower but more practical meaning of the word, entirely *in*sensitive. As such an example the illustration appended needs no comment.

2, 23, 24, 25, 234, 235, 245, 2345, ·
3, 34, 35, 345,
4, 45,
5,

which represent all possible combinations with five figures.

The composition of the preliminary (or "first test") bath was

Dyestuff (1:1000 sol. in alcohol)	2–7	cc,
Water	200	cc,
Ammonia	3	cc,

the variable amount of dye solution depending upon the number of components. All plates from this bath were bathed and dried without supplementary washing.

The type of plate selected for bathing was the Seed 27 "Gilt Edge," and the length of bathing was in every case three minutes.

Each of these plates (size $3\frac{1}{4}\times 4\frac{1}{4}$ inches) was then exposed to a series of diffused daylight spectra in the "standard" spectrograph[1] for 15 and 30 seconds, and 1, 2, 4, 8, 12, 16 minutes respectively; two supplementary exposures were also made, first, through an aesculin filter absorbing all wave-lengths shorter than λ 3968, the object being the avoidance of false conclusions in sensitiveness due to the overlapping of the second order ultra-violet. The second exposure was made through an ammonium picrate filter whose absorption ended rather abruptly at λ 5200, and with the collimator wedge in position, which displaced the spectrum relatively along the plate, thus bringing the B line about equally distant from the two edges. This latter exposure is of great value in determining *extent* of practical sensitiveness.

From the set of thirty-one "type-plates" thus secured (each containing nine spectra) twenty were selected for continued study as possessing particular interest, and with these the treatment was varied according to Table I.

The assignment of decimals was simply to facilitate the recording of results in the laboratory notebook. For example, type 14.11_e then represents a "27" plate bathed in pinacyanol + homocol, in a bath composed of water + alcohol + ammonia, and washed in alcohol; the subscript *e* refers to temperature and will be considered presently.

[1] For description of this instrument see former paper, previously referred to.

TABLE I

	Basic Constitution of Dye Bath	Subsequent Washing
0.1	Water	No washing
.2	Alcohol	No washing
.3	Water + Alcohol	No washing
.4	Water + Ammonia	No washing
.5	Alcohol + Ammonia	No washing
.6	Water + Alcohol + Ammonia	No washing
.7	Water	Water
.8	Water + Alcohol	Dil. alcohol
.9	Water + Alcohol	Alcohol
.10	Water + Ammonia	Water
.11	Water + Alcohol + Ammonia	Alcohol
.12	Water + Alcohol + Ammonia	Dil. alcohol
.13	Water + Alcohol + Ammonia	Water
.14	Water + Ammonia	Alcohol

Upon examination, this large number of plates was capable of furnishing very authoritative information upon certain combinations, which were therefore isolated and subjected to further study by varying the amount of dye in the component parts of the combination.

The influence of temperature of the bathing-solution and washing-bath was also investigated at temperatures ranging from 12° to 30° C., at which latter point the gelatin film partially dissolved, the series of subscript letters already referred to indicating the temperatures.

$a = 12°$ C.
$b = 15$
$c = 18$
$d = 20$
$e = 23$
$f = 24$
$g = 26$
$h = 30$

A second group of dyestuffs, consisting of

6. Orthochrome T.,
7. Cyanin,
8. Ethyl Violet,
9. Tetraiodofluorescein,
0. Ethyl Cyanin T.,

was handled in a similar but less extensive manner to Group 1 (twenty plates being made), and deductions from the spectra obtained thereon

allowed of a further reduction to ten, as showing probable interest in combination with the secondary and final selections of Group 1. These combinations were in turn made up, plates again bathed, and the spectrum photographed.

Besides the dyestuffs arranged in the two groups already referred to, a large number of others[1] were also experimented with in combination with those contained in Groups 1 and 2, but only such as present interest in connection with the main object of the present investigation

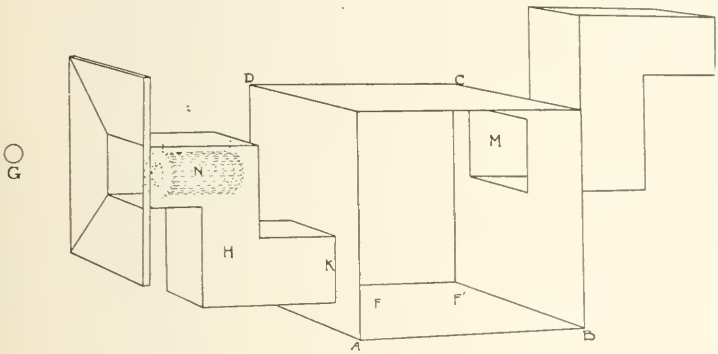


FIG. 1

are referred to throughout the succeeding portion of this paper. It may be stated, however, that the total number of plates exposed numbered 287 besides 40 for acetylene duplication and speed determination aggregating over 2500 separate exposures.

DRYING-CABINET

The bathing of all plates was conducted in total darkness (time being kept by means of an indicating metronome) and dried in a cabinet constructed especially for that purpose, and which may now briefly be described. Reference to the drawing will make the description sufficiently plain.

ABCD (Fig. 1) is a box closed in front by a light-tight door *E*, and containing two racks *FF'* in which were stood the plates to be

[1] Among the remaining dyes experimented with during the course of the present work may be mentioned Pinachrome Blue, Echt Rot, Rose des Alpes, Fluorescein (Monobromo-, Diiodo-, Tetrabromo-), Glycin Red, Acridin Yellow, Chinoline Red, Benzo Green, etc.

dried. A constant current of air, supplied by an electric fan at *G*, was driven through the rectangular elbow-tube *H*, and entered the box proper at *K*, passed between and over the plates at *FF′* and thence through *M* to the outer air. A skeleton coil of German silver resistance wire at *N* was supplied with current, and by this means the incoming air was heated and dried. In use the fan was boxed in by a rectangular wooden frame covered with muslin, which in practice served well to eliminate any trouble due to dust. The resistance coil was so wound that the heat generated in the drying-box averaged 32° C. after running for 30 minutes.[1] Separate switches for the fan and coil enabled either to be "cut in" independently.[2]

CHECK-PLATES AND SPEED

Examination of the final plates as to fitness for measurement also indicated the most interesting types, and of all plates thus selected their corresponding dye baths were again made up and a new series of plates bathed therein under precisely similar conditions as accorded with the former set. These plates were then cut in half; one section was exposed to the spectrum of a constant acetylene flame for a series of exposures of 1, 2, and 3 minutes while the spectrum of diffused daylight was impressed for 2 and 4 minutes at the top and bottom. The daylight spectra on this duplicate set served for two purposes: (1) as position indicators by means of the Fraunhofer lines, and (2) as a check upon the plates already noted in the first series. The acetylene flame spectrum simply served to show that the plates were *relatively* as noted, but cannot of course serve for measurement except between themselves, on account of the difference in chromatic intensity between this light and daylight.

The remaining section of the plate was exposed to daylight in the rotating sector machine,[3] together with an unbathed "27" plate of the same emulsion number, and they were developed together. From

[1] The wire used was B. and S. gauge No. 34, and the amount was approximately 20 ft.; the current was 110 volts, direct.

[2] The importance of rapid drying of battered plates has been pointed out by von Hubl (*Das Atelier*, 1906, p. 6) and also by E. Valenta (*Photo. Korr.*, September 1907) (also, *Brit. Jour. Phot.*, 54, 751, 1907). The drying-cabinet in use by the writer was constructed in July 1903, and has been in use since with unvarying success.

[3] See "Studies in Sensitometry. I," by the author.

this exposure was extracted the relative speed. In practice *three* bathed strips and one "27" were exposed and developed simultaneously.

After checking up the daylight plates with their corresponding acetylene plates, the former were measured in the spectro-photometer and their densities plotted as ordinates against wave-lengths as abscissae, selecting that spectrum exposure on each plate which corresponded to an approximate density of 2.5 in the blue-violet.

As has been stated, it is not intended to detail the results from all of the plates thus obtained, but instead, reference will be made to but two classes, viz., those which possess primary importance because of sensitiveness throughout the entire spectrum, and those which are important by reason of special sensitiveness for a limited spectral region. In both instances the relative sensitiveness-ratios are tabulated for as many positions as may be necessary to convey truthful impression of the results, while particular cases are subject to more complete measurement and graphically illustrated by their accompanying curves.

EVALUATION OF χ

It must be pointed out that while, at first sight, the value for χ has been recorded in apparently the same manner as pursued by Mees and Sheppard, viz., $\frac{\text{blue-sensitiveness}}{\text{yellow-sensitiveness}}$,[1] yet the value is arrived at in a somewhat different way, for while these workers obtain it as $\frac{\text{yellow-inertia}}{\text{blue-inertia}}=\frac{\text{blue-sensitiveness}}{\text{yellow-(or red) sensitivenes}}$, the value of such inertia having been obtained behind broad-banded filters, the present χ value is obtained from the ratio of the *densities* measured directly from the spectrum plate, and hence, relatively speaking, replaces qualitative values by quantitative. Thus, in the present instance

$$\chi=\frac{\text{density of blue at}\,\lambda\ 4100\ (=\beta)}{\text{density of}\ \lambda_n}.$$

It will therefore be noted that the lower the value of χ the higher the chromatic sensitiveness.

The shift in sensitiveness toward the red from the point of maxi-

[1] First advanced by Eder, *Beiträge zur Photochemie*, III. Theil, 126; also *Système de sensitométrie*, p. 133.

mum absorption of the dye, following Kundt's law,[1] and due to the high refractive index of the silver salts, has already been noted and commented upon by many writers; also, in view of the fact that the absorption of these later dyestuffs is very definitely known, the inclusion of further work upon this point has not been considered necessary.

NATURE OF PLATE USED FOR BATHING

It is a point often emphasized that there should be selected for bathing a plate which is originally "fog free," and several writers have advocated the use of slow plates as being conducive to the best results. In the course of the present work there were included Seed and Cramer lantern-slide plates, Seed "26x," Seed "23," Seed "process," and Cramer "Crown," besides special instances where use was made of Cramer "Instantaneous isochromatic" and Cramer "Trichromatic." The results from these plates, coupled with experience gained in plate-bathing and covering a period of fourteen years, lead me unhesitatingly to the rejection of slow plates as being wholly unsuited to the end in view.

It goes without question that initially the plate selected must be free from fog, but after the best possible effect has been obtained, i. e., the lowest value for $\frac{\beta}{\lambda_{RED}}$, it still follows that the point of maximum sensitiveness of any plate, due to the silver salts, will not be materially shifted from its original position unless (1) the dye taken up by the silver bromide and gelatin be in such amount that it exercises a selective screening effect upon the light incident upon its surface, or (2) by the introduction of some dye which (otherwise inert) is present solely for the purpose of acting as a color-filter.[2]

Eliminating from the discussion this latter phase,[3] and considering the former modified by the fact that the amount of active dye intro-

[1] A. Kundt, "Ueber den Einfluss des Lösungsmittels auf die Absorptionspectra gelöster absorbirender Medien, *Annalen der Physik*, 4, 53, 1878. See also Eder and Valenta, *Beiträge zur Photochemie*, III, 35.

[2] E. König, "Non-screen Orthochromatic Plates by Bathing," *Brit. Jour. Photo.*, 54, 786, 1907.

[3] Plates for astronomical and general scientific use must be of as high a speed as possible, whence it is impractical (from this standpoint) to consider the presence of a "screening" dye, as its action "slows" the plate.

duced is limited by reason of its negative sensitizing effect when in excess, we find the question considerably narrowed. It follows, then, that not only must the plate be free from fog, but it must also be so chosen that its development-factor for blue-violet light ($\gamma_{\infty\beta}$) be as low as possible; by this means we are enabled to attain the maximum of development action without excessive density in the blue-violet, and hence a more uniform action throughout the spectrum.

DEVELOPMENT

In but little of the work hitherto published is any mention made of the adoption of precautionary measures to insure the constant value of the factors controlling development. It is known that variation in development-time, temperature, or constitution will undoubtedly affect the values of the spectrum-curve, so that unless these constants be kept very rigorously exact, the value of the result will be vitiated to a greater or less extent depending upon the amount of variance. Throughout this work, therefore, the development of all plates was kept constant in constitution of developer and time of development, while the use of a water-bath of 70 liters capacity fitted with electric control assured steady temperature. The development tank is of thin glass, rectangular in shape, and all plates were handled and developed in total darkness.

Some consideration may now be given to the correct duration of development. It will be obvious that if any plate which possesses a high γ_∞ for the blue-violet region receives the minimum of exposure, it may, by continued development, be made to give the required density in that region without showing the true relative color-effect. On the other hand, the same plate may be exposed until the blue-violet region has reached the overexposed portion of the characteristic gradation-curve, and yet from development with a weak reducer, or from lack of sufficient length of development-time, it may in its densest part record a value even lower than the 2.5 necessary. Both plates would be equally untrue when considered as a record of relative sensitiveness.[1]

[1] J. Precht and E. Stenger, "Die Farbenwerte auf panchromatischen Platten in ihrer Abhängigkeit von der Entwicklungsdauer," *Zeitschrift für wissenschaftliche Photographie*, 3, 67, 1905.

Hurter and Driffield have shown[1] that in the gradation-curve of a photographic negative the true relation of the original light-values is obtained only when the development factor (γ) of the negative equals 1.0. If lower than 1.0 then the tonal values will be reproduced with too small a difference between them, while if greater than 1.0 then the differences will be exaggerated. At the same time it must not be lost sight of that the production of a negative is not the final stage in the photographic process, but merely the means to an end, which "end" is a positive proof whether it be on glass or paper. It is also a well-recognized fact that different positive processes require a different type of negative, i. e., more or less "contrasty," or, correctly speaking, of different γ value.

The greater the amount of development action (within limits) which a well-exposed plate receives, the higher becomes the value of the γ. In the recording of scientific data development is often forced in the endeavor to bring out faint detail which lies beyond the period of the straight portion of the characteristic curve, and is located in the region of underexposure, with the result that the more exposed portions of the plate become abnormally dense, and are generally subject to a later local reduction. In sensitometric tests, however, it is obvious that development should not be continued beyond the point where it is possible to reproduce the scale of values in its entirety.

It would appear, therefore, if $\gamma_{1.0}$ means that throughout the "straight" portion of the plate curve, the deposits are proportional to the logarithm of the light received, that such a value would be correct for the development of the spectrum exposures. Theoretically, the simplicity of such a solution is marred by the fact that it has been shown that the gradation-curve varies slightly with the wave-length of the light; so that it results from this that if $\gamma = 1.0$ at, say, the blue region, then in the yellow the value may be, say, $\gamma_{1.1}$.[2] In practice, however, the objection may be dismissed, as the variance involved is

[1] *Jour. Soc. Chem. Indust.*, May 31, 1890.

[2] Mees and Sheppard, in their *Investigations on the Theory of the Photographic Process* (Longmans, Green & Co., 1907), p. 307, arrive at the conclusion that γ remains unaltered by different wave-lengths, the alteration existing merely in the *shape* of the curve, and due principally to differences in the optical opacity of the film, resulting from different colored lights. See also article by E. Stenger, *Zeit. für Reproductionstechnik*, March 1906.

exceedingly small, and in work of this nature, when handled in the method proposed, becomes a vanishing quanity.

The great number of positive printing-media now available are called forth principally by the necessity of supplying the general worker with a means of obtaining presentable results from negatives which, from many reasons, have been improperly exposed or developed. In sensitometric work uncertainty of exposure and development has been eliminated, so that it simply remains to consider the process best suited for use. Such process is unquestionably that of a positive upon glass, and, therefore, the γ value of the negative must be altered to suit the capacity of the process, the amount and direction of such alteration depending upon the medium selected.

Taking only two examples from many media, let us consider development paper, on the one hand, and a transparent positive on glass, on the other.

Three sector-disk negatives were taken which had been developed for different times and had measured development-factor values of $\gamma_{0.87}$, $\gamma_{1.3}$, and $\gamma_{2.5}$ respectively. All three were printed simultaneously on "portrait velox" for 4, 6, 10, and 16 seconds, exposure being to a constant light-source. All four prints were then developed in rodinal.

Examination showed that it was possible to reproduce only one of the negatives so that all of the tones would show, viz., $\gamma_{0.87}$, the remaining two being too "contrasty," so that in printing for the tones involved in the higher densities, the other end of the scale was lost. A transparency, however, on a Seed "27" plate gave a complete scale of tones up to about 5.0 H. and D. units ($\gamma_{2.5}$).[1]

Now, if it be possible to print from a negative showing all tones between 0 and 5.0 it should (theoretically) be practical simply to develop the plate containing the series of spectrum exposures at the temperature and for the time necessary to reach a development-factor value of approximately 2.5. Objection to this course lies in the fact that although it is possible to measure in the neighborhood of this density, yet there is in the hands of the writer an unreliability attendant upon such measures, and they are rendered possible only by the intro-

[1] The value of 5.0 was obtained by extrapolation, this density being too high for measurement without the use of special methods.

duction of a supplementary measured density plate in the polarized beam. For convenience, therefore, and as being conducive to more reliable results, direct measurements are not made upon a density of higher value than approximately 2.5. Inasmuch as the slope of the gradation-curve is dependent principally upon the amount of development action, it suffices, then, that the spectrum plate be developed with the same developer, for the same length of time, and at the same temperature, as the sector-disk plate of same constitution which when measured records a value of $\gamma_{1.3}$. This method, although not absolutely exact, is sufficiently near truth to be accepted, when we take into consideration the accidental errors of the evaluation. By exposure of a plate of similar nature through narrow-banded filters it would be possible to obtain sensitiveness values for various limited regions, which with reference to the blue-sensitiveness could be easily calculated into a mean γ_n for use with the spectrum plate; but such a method would be a refinement possessing no truly practical value, and would require to be redetermined for every variation in the sensitizing bath.

It may be stated that a Seed "27" plate exposed to daylight in the sector-disk machine requires 3 minutes' development at a temperature of 20° C., with a solution of rodinal 1:24, in order to attain $\gamma_{1.3}$.

TEMPERATURE

The influence of the temperature of the sensitizing bath upon the plate was studied by making up bath 124, which was cooled by means of ice to a temperature of 12° C., and in which were then bathed two plates for 3 minutes and subsequently washed in alcohol at similar temperature for 30 seconds. The temperature of the bath was then raised by seven separate stages to 30° C., two plates being bathed at each step in the rise. All plates were then rapidly dried at the same temperature.

Exposure of each plate to the spectrum series of a constant acetylene flame showed a very interesting and clearly defined difference, which was borne out by a second series bathed on the following day and exposed to diffused daylight.

The following are the measurements of the principal plates in the series:

Temperature	Mean Density			$\chi = \frac{\beta}{\lambda\ 6500}$
	At λ 6500	At λ 5900	At λ 4300	
12°	1.3500	1.2440	2.3128	1.71
20°	2.1370	1.8160	2.2502	1.05
24°	1.8660	1.5206	1.7686	0.95
30°, plate melted				

and their accompanying curves (Fig. 2).

It therefore follows from the foregoing results that an increase in the temperature of the dye bath exercises a beneficial effect upon the relative chromatic sensitiveness of this plate. This effect has been confirmed in many other instances throughout the course of the investigation. The temperature of the bath is therefore kept constant at 23° C. Referring to the plates of different makes which have also been experimented with in this regard, it results, that although the effect is not identical with each, it yet appears to be uniformly certain with the Seed "27."

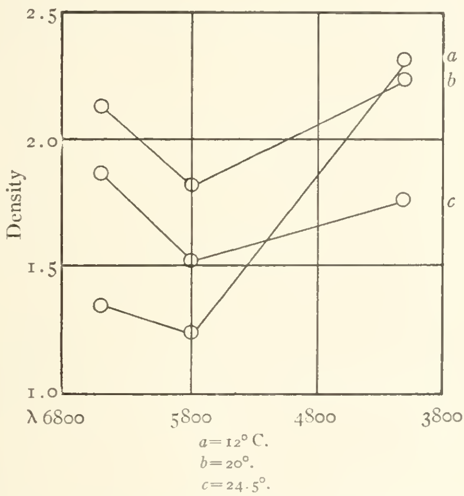


FIG. 2.—Acetylene flame (relative densities not comparable with other curves).

RESULTS

The principal results may now be briefly considered as follows:

Pinacyanol.—A plate bathed in an aqueous solution of this dye and washed in H_2O shows a strong sensitiveness to the spectrum from λ 3300–7000, and with increased exposure to beyond λ 7200, with two distinct maxima in the red and green at λ 5270–5800, and λ 6160–6870. The addition of NH_3 to the bath increases the red-sensitiveness to a considerable degree, and this increase is propor-

tional to the amount of NH_3 added. The introduction of ethyl alcohol to the dye bath, and omission of the subsequent washing, results in a distinctly greater action from λ 5270–5890, while the general effect upon the sensitiveness from λ 5270–6580 is shown by a decided increase in relative chromatic effect. A subsequent rinse in alcohol after bathing shows a still further improvement.[1]

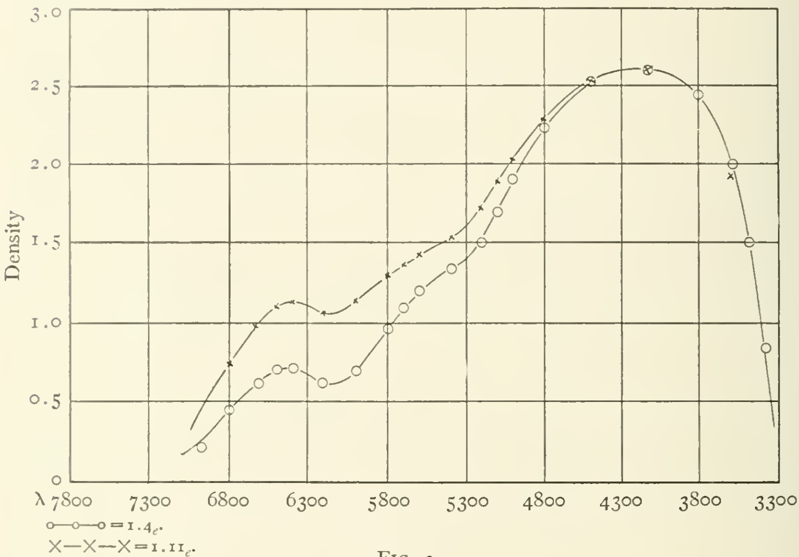


FIG. 3

Variation in the amount of dyestuff entering into the bathing-solution was experimented upon in amounts varying from 30 minims to 90 minims in steps of 10 minims. The greatest sensitizing action upon the "27" plate was found to follow when the amount of dye was $\frac{1}{68000}$ to $\frac{1}{70000}$, which is in close agreement with the experimental results of Mees and Sheppard.[2]

Fig. 3 shows the curve of this type-plate and illustrates the advantageous results following the addition of, and washing with, alcohol. The reduction in speed from the "27" is 0.19.

[1]The introduction of alcohol to the dye bath was published by Dr. E. König, who however treated the plate to a subsequent washing in water. *Photo. Korr.*, September 1905, p. 406.

[2] *Theory of the Photographic Process*, p. 327.

In obtaining the χ value for all of the following plates $\left(\frac{D\beta}{D\lambda_n}\right)=\chi$, λ 4100 $=\beta$, while $n=\lambda$ 5100, 5500, 5900, 6300, and 6800 respectively.

χ FOR PINACYANOL BATHED

Type \ λ	6800	6300	5900	5500	5100
1.11e.....	3.47	2.34	2.15	1.75	1.38
1.4e......	5.79	3.76	3.25	2.01	1.53

Pinaverdol.—This dye in dilute alcohol bath sensitizes for the green and orange-red of the spectrum extending to about λ 6400 (and with increased exposure to λ 6700), with two broad distinct maxima near

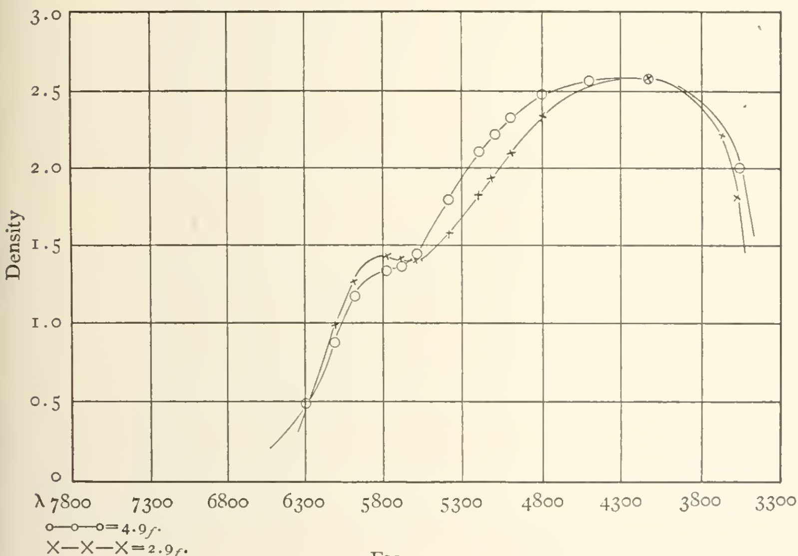


FIG. 4

λ 5900 and λ 5300. The best result from the use of this dye was obtained with a bath of the following constitution:

Pinaverdol 1:1000	60 minims
Methyl Alcohol	3 oz.
Water	4 oz.
Ammonia	60 minims

Time of immersion, three minutes—no washing. Speed difference = 0.60. See 2.9*j*, Fig. 4.

At λ=6300	5900	5500	5100
χ=5.73	1.79	1.75	1.31

Homocol.—This is a particularly interesting sensitizer for the green on gelatino-silver-bromide, embracing the entire region from λ 4860–5460, and when made up with dilute ethyl-alcohol bath followed by alcohol washing gives a plate working with exceptional clearness. Its action is very similar to pinaverdol although with equal exposure it does not sensitize so far into the red. As a sensitizer for the blue-green this dye has no equal (see Fig. 4, curve 4.9*j*).[1] Speed difference =0.61.

At λ=6300	5900	5500	5100
χ=5.20	1.97	1.60	1.17

Pinachrome.—In dilute ethyl alcohol plus ammonia bath this dye sensitizes for the yellow-green and orange and shows definitely the α and β bands characteristic of cyanin.[2] With normal exposure to the spectrum the sensitiveness extends to λ 6300 but can be forced to beyond λ 6500 (Fig. 5). Speed difference =0.36.

At λ=6300	5900	5500	5100
χ=25.7	2.01	1.68	1.83

Pinacyanol + pinaverdol.—These two dyes in combination result in a very good plate in which the characteristic pinacyanol gap in the blue-green is very greatly benefited. χ values for the various positions are given in Table A. The gradation values in this plate remain similar to the unbathed "27." Speed dif. =0.32.

Pinacyanol + homocol also forms a good combination and one which has been recommended by Monpillard.[3] When made up in dilute

[1] This curve is not in agreement with that published by Mees, Sheppard, and Newton (*Jour. Roy. Phot. Soc.*, 45, 266, July 1905). The difference results from the use of a dilute alcohol dye bath in place of an aqueous. An aqueous (ammoniacal) bath gave a similar result up to λ 4500 to that obtained by these workers.

The replacement of the ammonia by potassium carbonate (and other alkalies) as recommended by Dr. König (*Phot. Korr.*, September 1905) did not prove successful in the hands of the writer.

[2] The two absorption bands of cyanin have been termed respectively α and β by von Hubl. The former lies near λ 5900 while the latter is near λ 5450. Eder's *Jahrbuch*, 1905, p. 183; also *Jour. Roy. Photo. Soc.*, 46, 133, 1906.

[3] *Bull. Soc. Fran. Phot.* (2), 22, 132, 1906.

ethyl-alcohol bath without ammonia the action throughout the red and green although fairly even is yet weak when compared with that in the blue-violet. The introduction of ammonia, however, shows a steady gain in the red- and green-sensitiveness as the amount is increased. (The same effect is noticeable as the bathing-time is increased.) With normal exposure the sensitiveness extends slightly

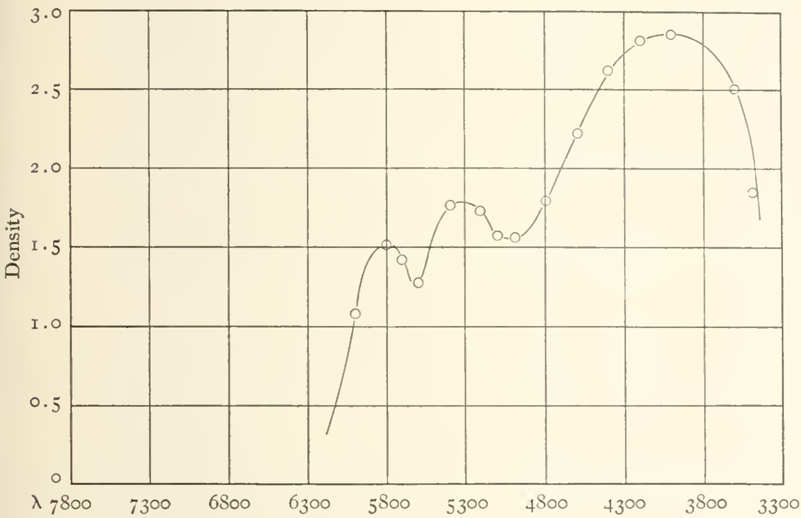


FIG. 5.—(3.11$_e$)

beyond B (λ 6870) while with increase in exposure it runs beyond *a* (λ 7200). From the blue the chromatic sensitiveness falls off rather abruptly and then pursues a fairly uniform curve which shows two distinct maxima at λ 5800 and λ 6400 respectively. Decrease in the amount of pinacyanol accentuates these maxima, the best result being obtained with a bath composed of

Pinacyanol (1:1000)	60 minims
Homocol	60 minims
Alcohol (ethyl)	3 oz.
Ammonia	90 minims
Water (dist.)	4 oz.

Another bath made up with the same proportionate amounts of dye, but containing a minimum quantity of water and excess of alcohol, shows a peculiar drop in the red-sensitiveness which ends at

λ 6560 very abruptly, and with an exceedingly pronounced drop in the orange at λ 6100, both drops becoming more pronounced as the dyes are increased in amount. A "27" plate treated in this bath resembles very closely in action the Seed "panchromatic" (see Fig. 6). When

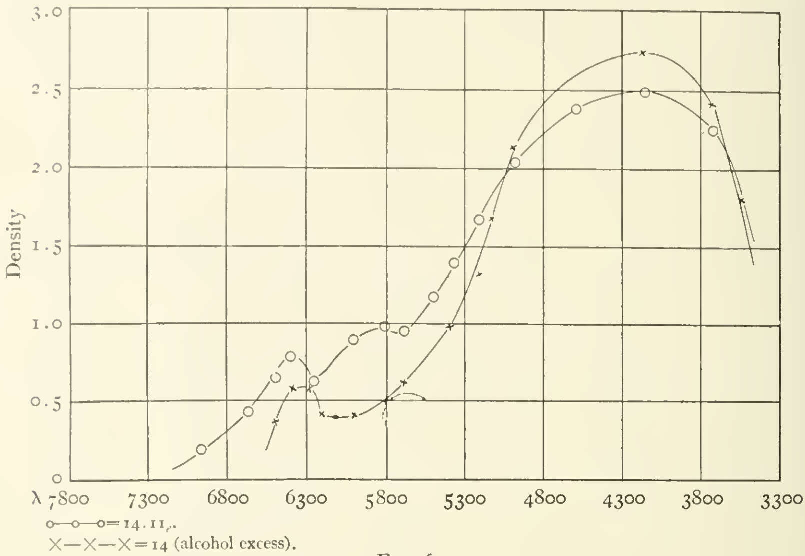


Fig. 6

made up in ammoniacal water bath the sensitizing action is very weak and unsatisfactory; this weakness is still more apparent when the plate is washed in water after staining, but shows a slight improvement when the washing is conducted with alcohol. Speed dif. = 0.74.

X

Type \ λ	6800	6300	5900	5500	5100
14.11$_e$..........	7.01	3.54	2.53	2.09	1.28
14. .... (Alcohol Bath)		4.40	5.91	3.16	1.47

Pinacyanol + pinaverdol + homocol.—This combination when made up in an aqueous ammoniacal bath and without supplementary washing sensitizes a "27" plate for practically the entire visible spectrum, extending easily to λ 7200. The usual gap in the blue-green is entirely

closed and the curve is fairly smooth throughout; washing the plate in water after staining, although increasing the speed, does not add anything to the chromatic value of the plate; a *slight* improvement is effected by an alcohol washing-bath. If the dye bath be made up with alcohol + ammonia the sensitizing action is weak and ill defined, and possesses no value whatever.

If the staining-bath be made up with dilute ethyl alcohol and ammonia we obtain a most excellent plate, with a markedly high red-sensitiveness and evenness of action. A brief washing in alcohol

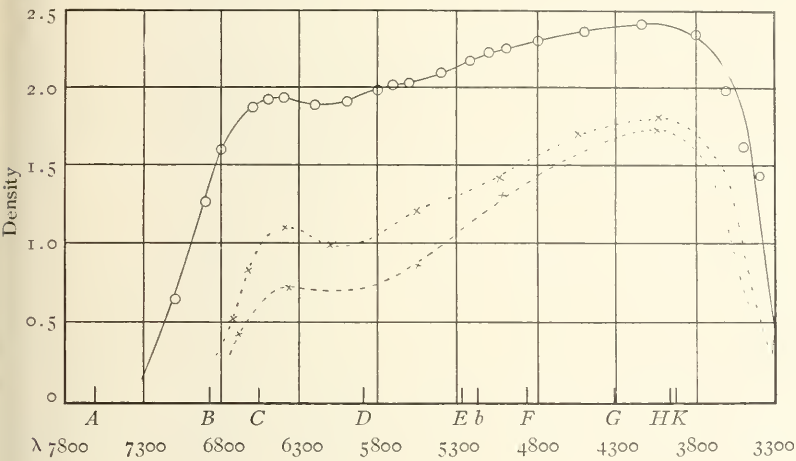


FIG. 7.—(124.11$_e$)

seems to be also very beneficial, no apparent difference showing (after exposure and development) whether this washing be continued for 20 seconds or 5 minutes.

Of all results obtained, this plate is decidedly the best, and for cleanness of working and general freedom from fog it leaves little to be desired. The bathing formula is as follows:

Pinacyanol	1:1000	50 minims
Pinaverdol	1:1000	40 minims
Homocol	1:1000	40 minims
Ammonia		120 minims
Alcohol		3 oz.
Water		4 oz.

Bathing-time 4 minutes; alcohol washing 30 seconds.

Fig. 7 shows the measured curve of this plate together with two underexposure curves showing the relative chromatic effect with reduced exposures; development, of course, remaining constant. Speed dif. =0.17.

Type 124.11e. χ

Exposure \ λ	6800	6300	5900	5500	5100
Normal.........	1.51	1.26	1.24	1.18	1.09
A.............	4.72	1.65	1.80	1.45	1.29
B.............	8.75	2.42	2.41	1.92	1.43

Speed difference = 13% in favor of the "27."

Pinacyanol + pinaverdol + dicyanin in ammoniacal water bath gives also a very good plate, although the action of the dicyanin seems to reduce greatly the general integral sensitiveness.[1] The blue-green

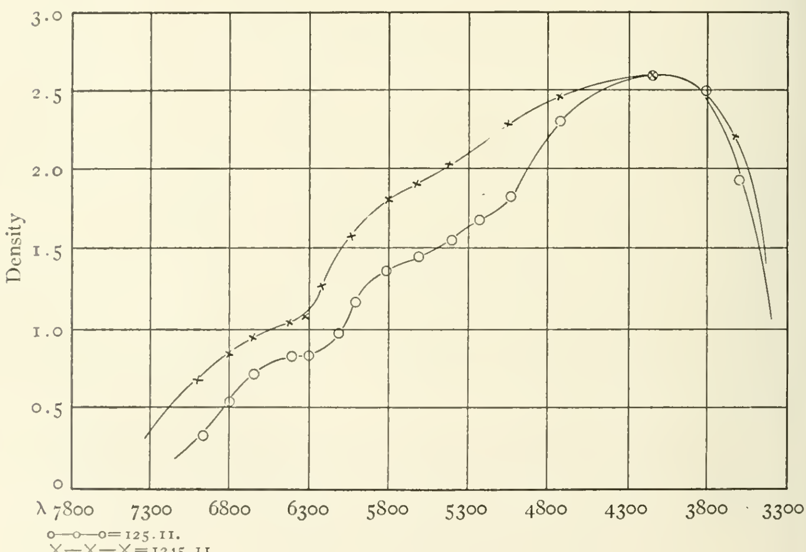


Fig. 8

insensitive gap is closed and the chromatic sensitiveness-curve descends toward the red in a good flowing sweep, the action extending to λ 7200

[1] This lowering of the general plate sensitiveness is noticed and commented upon by Monpillard, *Bull. Soc. Fran. Phot.* (2), 22, 1906; also *Jour. Roy. Phot. Soc.*, 46, 261, 1906.

with normal exposure but may easily be forced below Fraunhofer's A; on several plates the action is carried distinctly lower than λ 8400. Washing does not appear to influence the selective action in any way.

When the plate is treated to conform to .11 the sensitiveness to the red at λ 6500 and to the green at λ 5700 is increased, which adds materially to the value of the plate in general, although this increase is at the expense of the blue-green, which loses somewhat in sensitiveness. The plate works clean and bright, but does not keep. For sensitiveness-curve see Fig. 8. Speed dif. =1.64.

Type 125.11_e

At λ=6800	6300	5900	5500	5100
χ=4.72	3.07	2.00	1.76	1.49

The bath formula was as follows:

Pinacyanol	1:1000	30 min.
Pinaverdol	1:1000	60 min.
Dicyanin	1:1000	40 min.
Ammonia		120 min.
Alcohol		3 oz.
Water		4 oz.

Bathing-time=3 minutes; washing-time=30 seconds; temperature=23° C.

Pinacyanol + pinaverdol + homocol + dicyanin.—The introduction of homocol to the previous bath increases to a marked degree the general panchromatic quality and the sensitiveness is rendered much more even, although at the expense of speed (see Fig. 8). Speed dif. =0.91.

Type 1245.11_f

At λ=6800	6300	5900	5500	5100
χ=3.07	2.36	1.53	1.33	1.15

Pinacyanol + homocol + dicyanin.—The use of homocol in place of the pinaverdol in a type .11 bath and with a bathing-time of 4 minutes produces also a very good plate with a distinct lowering in the value $\gamma_{\infty\beta}$. This lowering of the density in the blue region was at first considered due to the solvent action of the ammonia on the silver salts but subsequent experiments seem to point instead to the action of the combined dyes as being the main factor influencing this reduction. This opinion must, however, be accepted with reserve, as sufficient

TABLE II

VALUES OF $\chi = \frac{r_\beta}{r_{\lambda_n}}$

Type	Dyestuffs	At λ 6800	At λ 6300	At λ 5900	At λ 5500	At λ 5100	Sensitiveness Limit (Normal Exposure)	Speed Reduction*
15.11.....	Pinacyanol + Dicyanin	6.52	4.10	2.75	2.65	2.11	7600	0.73
123.11.....	Pinacyanol + Pinaverdol + Pinachrom	5.49	3.18	2.20	1.66	1.48	6950	0.23
12345.11....	Pinacyanol + Pinaverdol + Pinachrom + Homocol + Dicyanin	4.22	3.36	2.43	1.83	1.48	7200	1.3
134.11....	Pinacyanol + Pinachrom + Homocol	2.82	2.44	1.79	1.60	1.47	6950	0.19
135.11.....	Pinacyanol + Pinachrom + Dicyanin	4.10	2.90	1.14	1.36	1.52	7200	1.25
1234.11....	Pinacyanol + Pinaverdol + Pinachrom + Homocol	5.40	3.13	2.17	1.71	1.38	7200	0.8
1345.11....	Pinacyanol + Pinaverdol + Homocol + Dicyanin	5.10	3.36	2.01	1.66	1.42	7500	1.0
1235.11....	Pinacyanol + Pinaverdol + Pinachrom + Dicyanin	3.95	3.33	2.31	1.81	1.31	7500	0.42
245.11....	Pinaverdol + Homocol + Dicyanin	5.01	4.07	1.83	1.47	1.07	7300	.61
235.11....	Pinaverdol + Pinachrom + Dicyanin	6.30	3.67	1.87	1.45	1.37	7400	.71
234.11....	Pinaverdol + Pinachrom + Homocol	3.95	2.79	2.14	1.62	1.37	7000	.68
25.11....	Pinaverdol + Dicyanin	5.80	5.75	2.31	1.65	1.37	7100	.81
24.11....	Pinaverdol + Homocol		3.36	1.66	1.38	1.14	6600	.41
23.11....	Pinaverdol + Pinachrom	4.11	3.47	2.0	1.52	1.43	6850	.62
34.11....	Pinachrom + Homocol		3.18	1.82	1.46	1.31	6300	.62
35.11....	Pinachrom + Dicyanin	10.2	5.04	2.52	1.65	1.54	7300	1.14
345.11....	Pinachrom + Dicyanin + Homocol	11.4	5.11	4.0	2.34	1.52	7500	1.11
45.11....	Homocol + Dicyanin	5.45	3.58	2.14	1.65	1.17	7500	
13.9	Pinacyanol + Pinachrom	3.36	2.81	1.77	1.55	1.48	6900	1.27
5.11....	Dicyanin	10.0	12.50	11.32	17.15	4.12	7300	0.94
6.9	Orthochrom T.		11.5	1.62	1.55	1.27	6100	.19
9.11....	Tetraiodofluorescein			13.4	1.74	3.65	5900	.39
0.7	Ethyl Cyanin T.	11.2	1.99	1.65	1.46	1.54	(Too low to be definitely stated)	.76
64.11....	Orthochrom T. + Homocol		10.4	2.09	1.38	1.48	6400	.41
61.11....	Orthochrom T. + Pinacyanol	6.42	3.71	2.17	1.79	1.51	6000	.24
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

work was not performed to confirm it, the type not being in direct line with the object sought.

The normal sensitiveness extends to λ 7200, although with but slight increase of exposure the great A group is clearly impressed. The plate is foggy if kept over a few days and must therefore be used immediately after preparation. A continued water wash after bathing gives a cleaner and better keeping plate but considerably reduces the

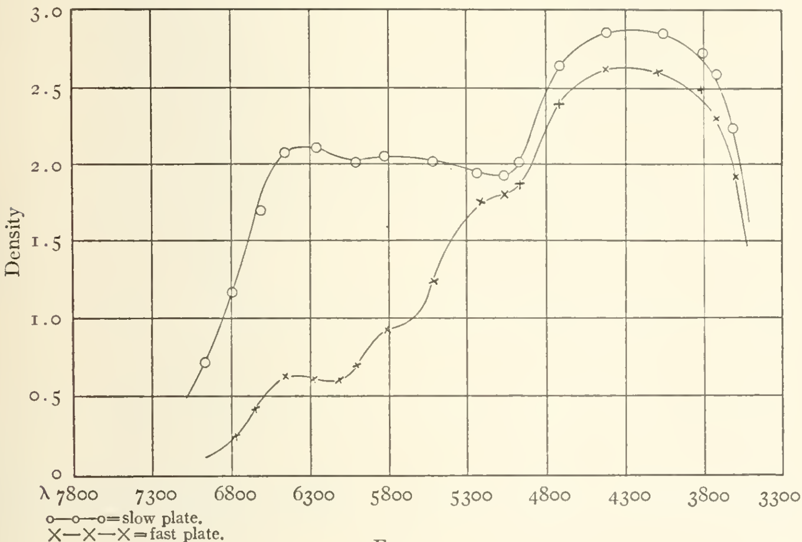


FIG. 9

speed. It may be mentioned that if the dye bath be made up with an aqueous ammoniacal solution (.7) and the plate be not washed after bathing, the same lowering of $\gamma_{\infty\beta}$ may be observed. Speed dif. =0.62.

Type 145.11_e. χ

At λ=6800	6300	5900	5500	5100
χ=3.34	2.32	1.82	1.66	1.38

Table II contains the χ values for the remaining plates of interest.

COMMERCIAL BATHED PLATES

Wratten "spectrum panchromatic."[1]—The consideration of orthochromatism by methods of bathing would be incomplete without notice

[1] Wratten and Wainwright, Ltd., Croydon, Surrey, England.

of this comparatively recent addition to the commercial-plate market. Undoubtedly, to the individual without previous experience in plate-bathing there is a certain amount of technical skill required for the successful production of bathed plates of uniform quality. Besides, there is the question of necessary accommodations, such as bathing-tanks and drying-cabinet, which very often prevent the taking-up of the work, more particularly by the individual who has only occasional use for such a product.

It is with the purpose of meeting just such conditions that these plates are prepared, and as they are *bathed* plates, it is proper that their consideration should find a place here.

These panchromatic plates are made in two grades: "fast" and "slow," and from a series of spectrum exposures, handled in precisely the same manner as the plates previously referred to, a series of measurements was made from which were plotted the curves shown in Fig. 9.[1]

χ FOR WRATTEN "PANCHROMATIC"

Type	At λ 6800	6300	5900	5500	5100
Fast	11.6	4.30	3.30	2.12	1.47
Slow	2.41	1.37	1.42	1.42	1.5

When reasonably fresh, the "fast" grade works with vigor and cleanliness, together with good freedom from fog, but like all bathed plates suffers deterioration as it is kept. The sensitiveness is good and at normal exposure pursues a fairly smooth curve extending beyond λ 6870; with increased exposure to beyond λ 7200. A normally exposed plate shows three distinct maxima situated at λ 5150, λ 4850, and λ 6400. The slow panchromatic is characterized by a remarkably low $\gamma_{\infty\beta}$. There is somewhat of a drop in the blue-green from λ 4860–5150, but from that point the curve rises with great evenness to λ 6600, whence it continues with gradually lowering sensitiveness on to about λ 7500. A is obtained with increased exposure. Unquestionably these are the finest panchromatic plates at present commercially obtainable, and the scientist or three-color worker who cannot prepare his own plates is certainly greatly indebted for the

[1] The writer here desires to express his thanks and appreciation to Dr. Mees, who courteously presented the plates.

enterprise manifested by their production. The inclusion here of their curves of spectral sensitiveness is necessary for purposes of direct comparison with other types under identical conditions.[1]

From the foregoing description and curves it will be seen that by far the best approximation to isochromatism is obtained in type 124.11_e. Further observation upon the behavior of the plate after bathing shows that it follows the general rule by suffering a decline in relative chromatic sensitiveness as its age increases. This retrograde action however is but slight for the first period (extending over several weeks) although distinctly noticeable after the lapse of two months. Measurement of a plate bathed at the same time as that plotted in Fig. 7 but kept for 60 days before exposure, shows a χ-difference as follows:

At $\lambda=6800$	6300	5900	5500	5100
$\Delta\chi=3.09$	0.39	.56	.25	.03

from which it follows that in order to obtain the very best effect the plates should be used when fresh.[2]

COMPENSATION FILTER

While the curve shown in Fig. 7 represents the best approximation to a true isochromatic value by means of the judicious selection of plate and dye bath, yet to be *absolutely* correct this curve should be a straight horizontal line. The advantages of a plate possessing such a curve of sensitiveness to those engaged in recording scientific data is sufficiently evident without detailed exposition. To approach this straight-line condition two courses are open: (1) the introduction to the film of a chemically inert dye whose function consists in staining the gelatin and thus acting as a color-filter; or (2) the use of a separate color-filter in the path of the incident light. This latter is (for the present purpose) decidedly the better method, because in the former case the integral speed of the plate is considerably lowered.

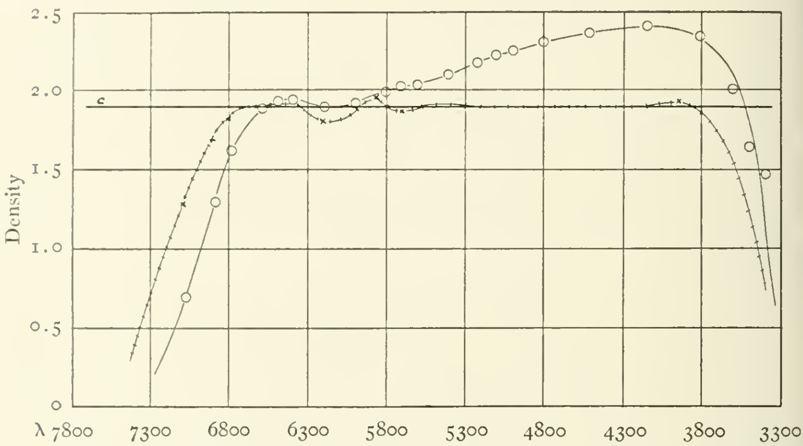
[1] The curve of the "fast" panchromatic, together with the χ value for the same, is very comparable with that plotted by Mees (*Brit. Jour. Phot.*, 53, 430, 1906), but only from λ 4700 to the limit of the red-sensitiveness. Owing (presumably) to the light-source, Mees' curve does not represent the true point of maximum sensitiveness, which should be at λ 4100 instead of λ 4700, the usual maximum for *AgBr*.

[2] For several months past this plate has been in almost constant use at this observatory in the records for the photographic photometry of colored variables, with results in every way satisfactory.

Repeating in Fig. 10 the sensitiveness-curve of Fig. 7, and drawing the horizontal path of the new (desired) sensitiveness-curve, we may obtain the extinction coefficient-curve of the color-filter necessary, by means of the simple formula

$$\frac{D-c}{\gamma}=e\ ,$$

where D = density of the plate at any given wave-length, c = the proposed new curve of sensitiveness, γ = the development-factor, and



o—o—o = curve of plate 124.11$_c$.

X—X—X = curve of same plate with compensation filter.

Fig. 10

e = the extinction-coefficient of the filter sought. As c in this instance is represented by a perfectly horizontal line, it is therefore sufficient to accept everything above that line as an absorption record of the filter required, if we now consider c as representing zero density.[1]

In the dye tartrazine we obtain the best agent for the selective absorption of the excessive density in the blue-violet, and ultra-violet as far as λ 3300 which is practically the limit of glass transmission. A spectrum photograph through an adjusted solution of this dye still

[1] In an able paper by André Callier the function and preparation of color-filters is very exhaustively treated, but while the methods and ideas therein expressed are deserving of the highest commendation, yet it must not be lost sight of that all of the curves and measurements are of prismatic spectra.—A. Callier, "Ecrans colorés," *Revue des sciences photographiques*, No. 10, 1906.

leaves much to be desired with reference to the red end, the drop at λ 6200 being quite apparent; this is, however, considerably improved by the introduction to the filter of a very small amount of napthylamine brown.

The best proportionate strength of solution yet arrived at is

	A.	Tartrazine	0.1 gram
		Water	100.0 cc
	B.	Naphthylamine Brown	0.01 gram
		Water	100.0 cc
Compensation filter=	A.	10 cc	
		Water 120 cc	
	B.	40.0 cc in a thickness of 5 mm	

The new curve of sensitiveness is shown in Fig. 10. The introduction of this filter, however, increases the exposure-time by the factor $\times 2.2$. For solar or laboratory absorption spectra this increase is a matter of no consequence. With bright-line emission spectra the use of the filter is unnecessary.

A series of daylight spectra with and without the interposition of the filter is shown in Plate XIV. As increase of exposure tends to a flattening of the curve, the compensated spectra shown are purposely underexposed.

Yerkes Observatory
November 5, 1907

A DETERMINATION OF THE MOON'S LIGHT WITH A SELENIUM PHOTOMETER

By JOEL STEBBINS and F. C. BROWN

Nearly all astronomical photometers are dependent upon the human eye or photographic plate for measures of light-intensity. It is the purpose of the present paper to present the results of experiments with selenium cells in a comparison of the moon's light with that of a standard candle. We have used a similar method for measures of starlight, but the results are reserved for a later publication.

As is well known, the crystalline form of selenium changes its electrical resistance when exposed to light, or under certain circumstances it gives an electromotive force when illuminated. For this latter reason, the crystalline form with electrodes attached was early named "selenium cell."

In 1895 G. M. Minchin[1] succeeded in measuring the current caused by light from bright stars in the focus of a two-foot reflector. The light was received by a layer of selenium immersed in oenanthol. E. Ruhmer[2] has used cells of his own manufacture in observations of solar and lunar eclipses. So far as we know, these are the only applications of selenium to astronomical photometry. A number of attempts have been made by physicists and electricians to perfect a practical form of "selenium photometer," but without success. The maximum sensitiveness of selenium is not in the yellow region of the spectrum, as is the case with the eye, and the effect of temperature changes is another drawback. Experimenters have usually been baffled by unexplained irregularities, some of which originate in the method of making the cells.

The essence of the method of observation used by the writers consists in exposing a cell, usually for 10 seconds, and noting the change of resistance by means of a galvanometer. By taking all precautions

[1] "The Electrical Measurement of Starlight," *Proc. Roy. Soc.*, 58, 142, 1895.

[2] "Ueber die Wahrnehmung der partiellen Sonnenfinsternis am 31. Oct. 1902 mittelst lichtempfindlicher Selenzelle," *Weltall*, 3, 63, 1902; "Ueber die Beobachtung der fast totalen Mondfinsternis am 11./12. April 1903 mittels lichtempfindlicher Selenzelle," *ibid.*, 3, 200, 1903.

suggested by an experience of several months, we have succeeded in obtaining consistent results. The cells used are those on the market by Giltay and by Ruhmer. Two wires are wound close together in a double spiral about a flat insulator, and the spaces on one face are filled with selenium which has been properly sensitized. The exact treatment used by Giltay or Ruhmer is not known to us, and is presumably a trade secret, but the annealing can be accomplished by heating the selenium in place to the melting-point, 217° C., and allowing it to crystallize between 100° and 200°. The constants of the cells are given in the following table:

TABLE I

Constants of Selenium Cells

Cell	Dimensions of Sensitive Face	No. of Wires to cm.	Resistance at 20° C.	Change per 1° C.
Giltay 93..........	50×26 mm	17	410,000 ohms	18,000 ohms
Ruhmer 619.......	47×50	20	470,000	27,000
Giltay 94..........	50×26	11	800,000	......
Remade Giltay.....	50×26	11	3,000,000	20,000

The wires across the sensitive face have the length given by the second dimension, while their number gives the width of the selenium elements. An increase of temperature lowers the resistance of the cells, as shown in the last column. We destroyed the sensitiveness of the fourth cell in some other experiments, and it was reannealed by Mr. Brown. Most of our observations have been taken with Giltay 93, but it was supplemented at times by the Ruhmer cell, and the others were used on only two or three nights.

The arrangement of the apparatus was simple. The cell was connected as one arm of a Wheatstone's bridge, the constant arms being 10 and 1000 ohms. The resistance of the fourth arm was therefore 1/100 that of the cell, and was varied to produce a balance. Current was supplied by two dry batteries giving 2.78 volts. The galvanometer is designated by its makers, Leeds and Northrup, as Type H, and is furnished with flat mirror, view telescope, and a millimeter scale at a distance 0.5 meter from the mirror. As used by us it has a dampening coil and is aperiodic. Under these conditions the galvanometer constant, number of amperes necessary to produce

one millimeter deflection, is 1.6×10^{-8}. The sensibility of the apparatus may be considerably increased by using higher resistances in the constant arms of the bridge, adding more battery, and substituting a more sensitive galvanometer. This would produce larger deflections due to light-action, but would also magnify all disturbing factors. After some months of experiences in trying to obtain steady conditions, we were satisfied to let well enough alone. Great care must be taken in the proper insulation of the apparatus, but as the resistances are high, no trouble was experienced from poor connections.

The standard candle is by Max Kohl and burns amylacetate. The diameter of the round wick is 8 mm, and the height of the flame is regulated to 40 mm. To eliminate air currents, the candle was placed in a blackened box with an opening at one end. To guard against sudden changes of temperature, the cells regularly used were inclosed in boxes covered with asbestos, and the light entered a glass window at one end of each box. Care was taken that the face of the cell was always normal to the incident light. The observers always worked in the same way, Mr. Stebbins making the exposures while Mr. Brown read the galvanometer.

After the electrical resistances were adjusted, the current was left on, and an exposure of the cell to light produced a deflection of the galvanometer. With Giltay 93, a 10-second exposure to the full moon gives about 160 mm. The exposures were made by hand while the observer listened to the one-second beats of a sounder connected with the observatory clock. Experiments in pressing a key under the same conditions show that a 10-second interval may be recorded on a chronograph with a probable error of 0.05 sec. We may assume with confidence that the probable error of an observed deflection, due to exposure-time, does not exceed 1 per cent.

The method of observation was to determine at what distance from the cell the standard candle would produce the same deflection as the light from the moon. Exposures at different distances from cell to candle were taken, and by graphical interpolation the required position was derived. No assumption was made as to the law of variation of the galvanometer deflection with intensity of light.

When possible the cell was first exposed several times to the moon, then followed a series of readings on the candle, and finally another

set on the moon. As the altitude of the moon was changing, the last series never agreed with the first, and it would have been better to "calibrate" with the candle both before and after the lunar observations; but the candle-power of the moon was not known in advance, and the danger from clouds made it imperative to begin with the object in the sky.

In Table II is given a portion of the work of a certain night, taken at random. The first column gives the order, next the Central Standard Time. The distance was measured directly from candle to face of cell, and the distance corresponding to the deflection obtained from the moon is given in parentheses. The mean deflections were plotted, and in this case the curve is nearly a straight line.

TABLE II

OBSERVATIONS WITH GILTAY CELL NO. 93

Friday, June 28, 1907. Resistance 430,000
Moon 48° past full. Temp. 19° C.

Order	Time	Source	Distance	Readings		Deflection	Mean Deflection
			m	mm	mm	mm	mm
1..........	$12^h\ 35^m$	Candle	4.50	7.0	75.0	68.0	....
12..........	15 08	Candle	4.50	25.7	91.3	65.6	66.8
4..........	13 26	Candle	5.00	14.3	72.0	57.7	....
5..........	13 38	Candle	5.00	17.9	75.2	57.3	57.5
8..........	14 25	Candle	5.50	20.7	68.9	48.2	....
9..........	14 39	Candle	5.50	21.6	70.4	48.8	48.5
2..........	12 56	Moon	....	4.0	57.0	53.0	....
3..........	13 06	Moon	(5.26)	4.9	57.3	52.4	52.7
6..........	13 50	Moon	....	23.0	87.0	64.0	....
7..........	14 03	Moon	(4.66)	21.3	84.5	63.2	63.6
10..........	14 49	Moon	....	22.5	88.1	65.6	....
11..........	15 00	Moon	(4.51)	24.0	91.4	67.4	66.5

The agreement of the deflections in each pair is very good, and from residuals furnished by these and similar observations may be derived a probable error of approximately 1 per cent. for a single deflection. This is perhaps misleading, and a better test is furnished by the agreement of results on separate nights.

It is necessary to wait for the cell to recover after exposure to a bright light. The first reading was always rejected, and all subsequent exposures were made at nearly the same stage of recovery, as indicated by the galvanometer reading. Near full moon, about five

minutes between exposures were given, while only one minute or less was required for faint lights. In the above sample, the progressive change of the galvanometer zero was due, at least partly, to temperature effect.

The variation of the moon's light with change of phase has not been studied since the time of Zöllner.[1] With a polarizing photometer, he derived the form of the intensity-curve between half and full moon. His results and those of previous visual observers have been summarized by Müller.[2] The observations with selenium cells by the writers during the summer of 1907 give a new determination of the curve of variation with phase, and also the candle-power of the full moon. Before discussing the results, the method of computing the phase, and of applying the necessary corrections will be given.

The phase is counted from full moon, and was computed from the equation

$$\cos \epsilon = -\cos(\lambda - \odot)\cos\beta \,,$$

where ϵ is the elongation of the moon from the point opposite the sun, measured on a great circle and considered negative before full moon. The angular phase of the darkened portion of the moon is always within 10′ of the value of ϵ. λ and $\odot$ are the longitudes of the moon and sun respectively, and β is the moon's latitude, all taken from the *American Ephemeris*. The effect of parallax of the moon upon the phase, which never exceeds 1°, may be neglected.

The reduction to mean distance of moon and sun has been accomplished by the following:

$$\text{Reduction to mean distance} = \frac{L_0}{L} = \left[\frac{P_0 \cos(h+P)}{P}\right]^2 R^2 \,,$$

where L is the observed and L_0 the corrected brightness of the moon, P_0 the mean equatorial parallax, 57′.0, and P the moon's actual parallax at the altitude h. The factor R^2 reduces to mean distance of sun. A table was prepared giving the logarithm of the term in brackets for each 10° of altitude, and each 1′ of horizontal parallax from 53′ to

[1] "Resultate astrophotometrischer Beobachtungen," *Astronomische Nachrichten*, 66, 225, 1866.

[2] *Die Photometrie der Gestirne*, Leipzig, 1897, p. 340.

62′. Log R is taken from the *Ephemeris.* In this method we have assumed the earth to be a sphere, and have neglected the moon's varying distance from the sun through the month, which may affect the result by half of one per cent.

The correction for atmospheric absorption may be represented by

$$\phi(z)=0.4a(\sec z-1),$$

where $\phi(z)$ is the logarithm of the reduction to zenith, and the factor 0.4 is inserted to change from stellar magnitudes to common logarithms. This expression for the absorption has been used for many years at Harvard, where the value of the coefficient a is determined on each night, and is found to average not far from 0.25. For zenith distances less than 75°, $a=0.23$ represents within one per cent. the mean absorption at Potsdam as given by Müller.[1] A rough determination of the absorption is possible from our own observations. On each night, the first and last measures of the moon's light give an equation of the form

$$\log L_2-\log L_1=0.4a(\sec z_1-\sec z_2),$$

where L_1 and L_2 are the candle-powers of the moon at the zenith distances z_1 and z_2. A least-square reduction of the observations on 13 nights, with Giltay 93, gives

$$a=0.50\pm0.26,$$

the large probable error being due in part to the small coefficients which enter into the equations, z_1 never differing by more than 8° from z_2.

This larger value of a produces more accordant results for each night, but the final curve of the moon's light is not improved, and we therefore adopt the absorption correction for mean conditions at Potsdam as given by Müller. This is not much better than a guess at the absorption, as we know that the color-sensibility curves of our cells are probably different from each other, and from that of the eye. Except for the judgment of the observers there was no check upon the variation of the absorption from night to night. No observations were taken through cloud or haze, but we found it extremely difficult to estimate the transparency of the air under different conditions of

[1] *Loc. cit.*, p. 516.

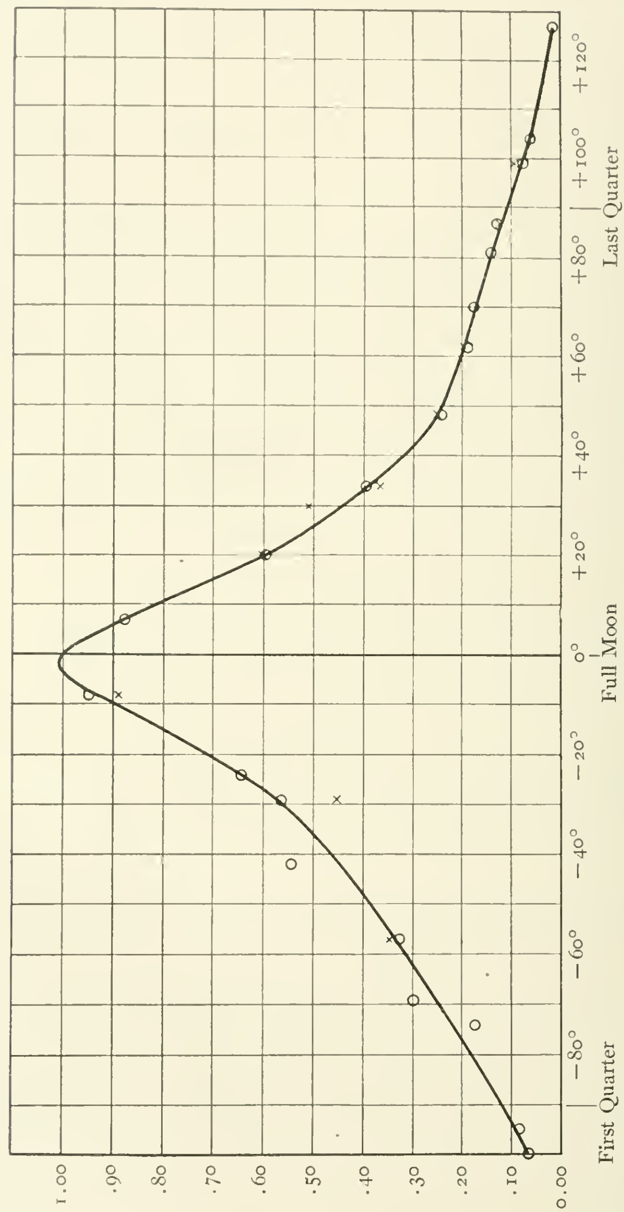


FIG. 1.—Relative Brightness of the Moon at Different Phases

moonlight. For this reason, if for no other, the results of the present paper can be regarded as only preliminary, and we hope to devise an independent method of determining the absorption.

In Table III are given the observations, reduction, and results from different cells, the headings being self-explanatory. The zenith distance was measured at intervals with a small transit, which is easier than to compute it. Its value for the time of each photometric observation was taken from a plotted curve, and is correct within one or two tenths of a degree. The number of exposures refers to the moon, and, since the calibration with the candle was equally important, no attempt has been made to assign different weights to the means. The corrected candle-power is the number corresponding to the sum of the logarithms in the three columns preceding it. In the next to last column is given the brightness in terms of that of the full moon, which is afterward shown to be 0.209 c.-p. for Giltay 93, and 0.0677 for Ruhmer 619.

The results are shown graphically in Fig. 1, where circles represent the observations with Giltay 93, and crosses those with Ruhmer 619, half-weight being assigned to the latter. It will be noticed that there is evidence that the moon is brighter between first quarter and full, than in the corresponding phase after maximum. This came as a complete surprise to the observers, but a glance at the full moon will show that there are more dark areas on the east than the west half, and in particular the third or southwest quadrant is brightest of all. Lord Rosse[1] found that the heat radiation is probably greatest before the full phase, and although Zöllner's curve of light-variation is symmetrical, he rejected one observation which accords with our work. The ends of the curve are necessarily uncertain on account of the low altitudes of the moon in those phases, but the curve can be prolonged to the known value zero at $\pm 180°$. The form near full moon has been drawn as well as possible with the data at hand. Obviously, at opposition the moon may lack 5° of being completely illuminated, and can approach only to about $1°.5$ from the center of the earth's shadow without touching the penumbra. The discordant observa-

[1] "On the Radiation of Heat from the Moon, the Law of Its Absorption by Our Atmosphere, and of Its Variation in Amount with Her Phases," *Phil. Trans. Roy. Soc.*, 163, 587, 1873.

TABLE III

BRIGHTNESS OF THE MOON WITH SELENIUM CELLS

Giltay Cell No. 93

Date	G. M. T.	Zenith Distance	No. of Exposures	Deflection	Distance of Candle	Log Candle-Power at 1 Meter	Log Reduction to Zenith, ϕ (z)	Log Reduction to Mean Distance	Corrected Candle-Power	Mean Candle-Power	Full Moon = 1.000	Phase
1907				mm	m							
June 23....	16^h41^m	59°.1	4	136.0	2.77	9.115	0.087	9.951	0.142	.....	.....	....
23....	17 47	62.7	4	120.0	3.02	9.040	0.110	9.951	0.126	0.134	0.641	−24°
24....	19 39	70.3	1	152.1	2.53	9.194	0.184	9.946	0.211	.....	.....	....
24....	19 54	71.8	1	145.1	2.61	9.167	0.204	9.946	0.208	.....	.....	....
24....	20 20	74.6	1	120.0	3.00	9.046	0.252	9.947	0.176	0.198	0.947	− 8
25....	19 57	67.0	2	153.6	2.63	9.160	0.146	9.944	0.178	.....	.....	....
25....	20 37	70.4	2	149.4	2.68	9.144	0.185	9.945	0.188	0.183	0.876	+ 7
26....	19 44	63.0	2	126.2	3.04	9.034	0.112	9.947	0.124	.....	.....	....
26....	20 32	65.3	2	125.1	3.07	9.026	0.130	9.948	0.127	0.125	0.598	+20
27....	19 30	61.6	3	93.8	3.70	8.864	0.102	9.954	0.0832	0.0832	0.398	+34
28....	19 01	65.2	2	52.7	5.26	8.558	0.129	9.967	0.0451	.....	.....	....
28....	19 56	60.2	2	63.6	4.66	8.663	0.093	9.965	0.0526	.....	.....	....
28....	20 54	57.0	2	66.5	4.51	8.692	0.076	9.964	0.0540	0.0506	0.242	+48
29....	20 06	60.2	2	48.5	5.56	8.510	0.093	9.978	0.0381	.....	.....	....
29....	20 51	56.0	2	52.4	5.27	8.556	0.071	9.978	0.0403	0.0392	0.188	+62
July 1....	20 28	62.7	2	34.4	6.98	8.312	0.110	0.006	0.0268	.....	.....	....
1....	20 44	60.4	2	36.4	6.78	8.338	0.094	0.006	0.0274	0.0271	0.130	+87
2....	20 30	66.5	2	21.1	9.45	8.049	0.141	0.019	0.0162	.....	.....	....
2....	20 46	63.5	3	21.6	9.20	8.072	0.116	0.019	0.0161	0.0162	0.078	+99
17....	15 21	68.0	2	20.6	9.17	8.075	0.156	0.006	0.0173	.....	.....	....
17....	15 30	69.5	3	20.9	9.09	8.083	0.174	0.006	0.0183	0.0178	0.085	−95
19....	16 06	67.3	4	61.8	4.64	8.667	0.149	9.980	0.0625	0.0625	0.299	−69
20....	14 44	58.0	3	81.0	3.86	8.827	0.081	9.966	0.0748	.....	.....	....
20....	16 17	65.5	5	66.0	4.52	8.690	0.132	9.968	0.0617	0.0682	0.326	−57
21....	17 56	72.6	2	92.7	3.60	8.887	0.217	9.958	0.115	.....	.....	....
21....	18 01	73.5	2	87.5	3.72	8.859	0.232	9.958	0.112	0.114	0.545	−42
22....	15 35	62.6	3	123.8	3.11	9.014	0.109	9.949	0.118	0.118	0.565	−29

TABLE III—*Continued*

Date	G. M. T.	Zenith Distance	No. of Ex-posures	Deflection	Distance of Candle	Log Candle-Power at 1 Meter	Log Re-duction to Zenith, $\phi(z)$	Log Re-duction to Mean Distance	Corrected Candle-Power	Mean Candle-Power	Full Moon = 1.000	Phase
1907				mm	m							
July 29....	21h 12m	43.5	3	49.6	5.40	8.535	0.031	0.000	0.0368	0.0368	0.176	+70°
30....	20 00	56.0	2	29.2	6.40	8.388	0.071	0.015	0.0298	0.0298	0.143	+81
Aug. 1....	20 36	60.0	5	11.8	10.5	7.958	0.092	0.038	0.0122	.....	.....	....
1....	21 22	51.4	5	14.0	9.20	8.072	0.053	0.035	0.0144	0.0133	0.064	+104
3....	21 07	67.8	5	2.8	21.0	7.356	0.154	0.053	0.0037	.....	.....	....
3....	21 15	66.5	5	2.1	23.2	7.269	0.141	0.052	0.0029	.....	.....	....
3....	21 31	63.4	3	2.5	22.0	7.315	0.115	0.052	0.0030	0.0032	0.015	+127
15....	14 48	73.3	4	7.8	11.1	7.909	0.228	9.994	0.0135	0.0135	0.065	−100
17....	15 14	68.5	4	39.1	5.85	8.466	0.162	9.972	0.0398	.....	.....	....
17....	15 45	72.6	3	30.8	6.95	8.316	0.217	9.973	0.0321	0.0360	0.172	− 74
Ruhmer Cell No. 619												
June 24....	18 38	64.5	4	21.4	4.48	8.697	0.123	9.945	0.0582	.....	.....	....
24....	19 24	68.9	3	20.6	4.56	8.682	0.166	9.946	0.0622	0.0602	0.889	− 8
26....	20 22	64.7	2	16.2	5.38	8.538	0.125	9.948	0.0408	0.0408	0.603	+20
27....	19 44	61.0	2	21.4	6.75	8.341	0.098	9.954	0.0247	0.0247	0.365	+34
28....	18 47	66.7	2	10.6	8.73	8.118	0.143	9.967	0.0169	.....	.....	....
28....	19 11	64.2	1	11.8	8.45	8.146	0.121	9.966	0.0171	.....	.....	....
28....	19 38	61.8	2	12.4	8.35	8.157	0.104	9.966	0.0169	.....	.....	....
28....	20 32	58.0	2	13.2	8.17	8.176	0.081	9.965	0.0167	0.0169	0.250	+48
29....	20 58	55.3	3	9.6	9.15	8.077	0.068	9.978	0.0133	0.0133	0.196	+62
July 1....	21 18	55.3	4	6.4	12.0	7.842	0.068	0.007	0.0083	0.0083	0.123	+87
2....	21 02	60.7	3	3.8	14.0	7.708	0.096	0.018	0.0066	0.0066	0.097	+99
20....	14 59	58.6	2	12.5	6.47	8.378	0.084	9.966	0.0268	.....	.....	....
20....	15 59	63.7	4	8.5	7.80	8.216	0.117	9.967	0.0200	0.0234	0.346	−57
22....	15 44	62.5	2	15.4	6.15	8.422	0.108	9.949	0.0301	.....	.....	....
22....	17 28	66.2	2	15.0	6.22	8.412	0.138	9.949	0.0316	0.0308	0.455	−29
26....	19 47	54.5	3	23.2	5.53	8.515	0.065	9.959	0.0346	0.0346	0.511	+30

TABLE III—*Continued*

Giltay Cell No. 94

Date	G. M. T.	Zenith Distance	No. of Exposures	Deflection	Distance of Candle	Log Candle-Power at 1 Meter	Log Reduction to Zenith, $\phi(z)$	Log Reduction to Mean Distance	Corrected Candle-Power	Mean Candle-Power	Full Moon = 1 000	Phase
				mm	m							
July 22....	18^h00^m	68.6	3	55.3	2.96	9.057	0.348	9.950	0.226	0.226	.....	− 29°
26....	20 16	54.5	2	69.0	2.59	9.173	0.144	9.959	0.189	.....	.....	....
26....	20 59	55.5	2	57.8	2.92	9.069	0.153	9.959	0.152	0.170	.....	+ 30
Aug. 1....	21 33	49.5	5	9.8	7.60	8.238	0.108	0.034	0.0240	0.0240	.....	+104
					Remade Giltay Cell							
July 20....	16 54	70.0	3	3.6	5.40	8.535	0.385	9.970	0.0776	.....	.....	....
20....	17 05	71.5	3	3.2	5.90	8.458	0.430	9.970	0.0721	0.0748	.....	−57
22....	17 38	66.7	4	7.4	3.78	8.845	0.306	9.949	0.126	0.126	.....	−29

tions at phases $-42°$ and $-74°$ were taken at zenith distances greater than 70°, and the uncertainty of the absorption must be the cause of these large deviations. The general agreement of the plotted points with the curve is perhaps an indication of the reliability of our results, and with uniform conditions the accordance of measures with selenium is at least equal to that of visual observations.

One of the interesting facts which may be seen in the curve is that the full moon is approximately nine times as bright as the half moon. The flashing out of the full moon has long been ascribed to the rough character of its surface, and it is evident that any mathematical theory of the light-variation will be complicated by the irregularity of the lunar features. The expression which Zöllner derived for the variation of the moon's light has been shown to be a mere interpolation formula.

Inasmuch as the selenium photometer is still in the experimental stage, it does not seem worth while to compare at length our work with that of visual observers. Table IV gives the variation derived from our curve, and a comparison with that of Zöllner, where his

TABLE IV

BRIGHTNESS OF THE MOON AT DIFFERENT PHASES

Phase	Observed	Zöllner	O.−Z.
−100°	0.06	....	......
− 90	.12	....	......
− 80	.18	....	......
− 70	.25	0.17	+0.08
− 60	.32	.24	+ .08
− 50	.38	.33	+ .05
− 40	.46	.44	+ .02
− 30	.56	.56	.00
− 20	.71	.70	+ .01
− 10	.90	.85	+ .05
0	1.00	1.00	......
+ 10	0.81	0.85	− .04
+ 20	.60	.70	− .10
+ 30	.44	.56	− .12
+ 40	.32	.44	− .12
+ 50	.24	.33	− .09
+ 60	.20	.24	− .04
+ 70	.17	.17	.00
+ 80	.14	....	......
+ 90	.11	....	......
+100	.07	....	......
+110	.05	....	......
+120	.03	....	......

values are as given by Müller, and the logarithms are reduced to numbers to correspond with our adopted values.

To determine the brightness of the full moon, the corrected candle-powers in Table III were plotted, giving a curve similar to Fig. 1. From the observations with Giltay 93, we derive 0.209 c.-p. for the full phase. Due to what must be a different color-sensitiveness, the Ruhmer cell invariably gives the candle-power of the moon about one-third as great as is found with Giltay 93. The ratios on different nights are as follows:

June 24	0.304
June 26	0.326
June 27	0.297
June 28	0.334
June 29	0.339
July 1	0.306
July 2	0.407
July 20	0.343
July 22	0.261
Mean	0.324

Multiplying the result from Giltay 93 by 0.324, the brightness of the full moon given by Ruhmer 619 is 0.0677 c.-p., and in the same way have been derived the results for the other cells. The adopted values, rounded off to two places, are as follows:

TABLE V

CANDLE-POWER OF FULL MOON

Cell	Candle-Power	Thickness of Glass
Giltay 93	0.21	1.1 mm + 3.3 mm
Ruhmer 619	0.07	2.6 + mica
Giltay 94	0.37	1.1
Remade Giltay	0.23	1.1

The thicknesses of the protecting pieces of glass or mica are inserted to show that no appreciable effect is due to them. The results of visual observers vary from 0.16 to 0.30 c.-p., and Müller[1] adopted a mean value of 0.23 c.-p. This happens to agree closely with the mean of our four cells, but the discrepancies above shown are inherent in

[1] *Loc. cit.*, p. 338.

the nature of the cells, and are not due to accidental errors of observation. We propose to determine the color-curve of each cell, but this will require some time, and the phase-variation of the moon's light is presumably about the same for all colors. It should be noted that our values include the effect of the bright background of the sky, which from some rough measures we estimate to be of the order of 5 per cent. of the total.

It was planned to observe the partial lunar eclipse of July 24, 1907, but unfortunately the night was cloudy. At intervals the moon was seen through clear spaces from 5° to 20° wide, and a few exposures were made. Great care was taken that no light cloud interfered. The deflections obtained were as follows:

TABLE VI

Observations with Giltay Cell No. 93 during Partial Lunar Eclipse, July 24, 1907

G. M. T.	Deflection
$16^h\ 02^m$	49.3 mm
16 04	43.7
16 06.5	43.1
16 29	36.4
16 31	36.6
16 33.5	37.6
16 35	37.9
16 36	38.3
17 07	87.1
17 07.5	87.3

The above values were plotted, and neglecting the effect of differential absorption due to the moon's changing altitude, the instant of least light, derived from times of equal deflection, was found to be $16^h\ 23^m$. According to the *Ephemeris*, the middle of the eclipse came at $16^h\ 22^m.4$, but this close agreement is partly accidental under the circumstances.

The original article by Ruhmer is not available, but from references it seems that his cell was continually exposed during the eclipse. Our experience with selenium has been that the best results are secured with short exposures.

SUMMARY

1. It has been shown that selenium cells can be used for accurate photometric measures of objects about as bright as the moon, and the results are at least as accordant as those from visual observations.

2. From a comparison of the moon with a standard candle, has been derived the variation of moonlight with phase. The full moon gives us approximately nine times as much light as the half moon, and the gibbous disk is brighter before than after full moon.

3. The candle-power of the full moon, as measured with selenium cells, is of the same order as that obtained by visual observers; but different cells give discordant values, which probably depend upon the different color-sensibility of the cells.

4. With the aid of a selenium cell, the central phase of a lunar eclipse was determined within one minute of the predicted time.

In conclusion we beg to acknowledge our indebtedness to Professor A. P. Carman of this university, who placed the facilities of the physical laboratory and shop at our disposal.

University of Illinois Observatory
September 1907

ON THE SPECTRA OF TWO METEORS

By S. BLAJKO

In 1904 I constructed a prismatic camera from a Voigtländer euryscope of aperture 50 mm and focal length 300 mm, and a prism of crown glass with a refracting angle of 45°. During the exposure of the first plate with this instrument, on May 11, 1904, a bright meteor appeared in the field of view of the camera and its spectrum was obtained. The driving clock had been regulated to sidereal time, and the stellar spectra therefore appeared as fine narrow streaks parallel to the hour circle passing through the center of the plate. The lines of hydrogen may readily be seen as interruptions in the streaks in the case of stars of the first spectral type. The co-ordinates of the center of the plate are: $\alpha = 0^h\,40^m$, $\delta = +80.^\circ0$, referred to the equinox of 1855; to which all other right ascensions and declinations in this paper are referred, as the photographs were compared with the charts of the *B.D.*

The spectrum of the meteor consists of fine lines of different degrees of brightness which lie parallel to each other from one edge of the plate ($\alpha = 21^h\,52^m$, $\delta = +78.^\circ0$) to the other ($\alpha = 4^h\,50^m$, $\delta = +80.^\circ5$), and are curved on account of the action of the prism, their average inclination to the direction of the stellar spectra being about 78°. The lines are much broadened from the position, $\alpha = 4^h\,20^m$, $\delta = +81.^\circ2$. A sudden increase in brightness obviously occurred at this moment; there was no noticeable increase in the number of spectral lines, merely the brightness increased. No trace of a continuous spectrum can be seen.

The apparent path of this meteor among the stars was obtained with the photographic camera (an Aplanat of Steinheil of free aperture 97 mm and focal length 640 mm) which has been employed here in recent years for the systematic photography of the heavens. It was this time directed intentionally toward about the same region of the sky as was the prismatic camera. The track of the meteor, which is almost a straight line, brightens from one edge of the plate ($\alpha = 20^h\,46^m$, $\delta = +67.^\circ0$) to the other ($\alpha = 0^h\,55^m$, $\delta = +83.^\circ0$). The co-ordinates of the center of the plate are $\alpha = 20^h\,12^m$, $\delta = +77.^\circ3$.

By accident I saw this meteor at the end of its appearance; it was of about the first magnitude or somewhat brighter, and of a yellow color; the train it left behind was about 25° long and was visible for about three seconds, at $12^h\ 36^m$, Moscow Mean Time.

Encouraged by this fortunate chance, I directed both instruments toward the radiant of the Perseids on August 12, 1904. During the exposure at $13^h\ 6^m$, Moscow Mean Time, there appeared a bright Perseid which was observed by Mr. Taschnow and myself. During the latter half of its path, after its brightness had undergone a sudden increase, it was nearly of the first magnitude and was of a pure-green color. Its spectrum and its path among the stars were photographed, the position of the center of the two plates being: $\alpha=3^h\ 17^m\ 21^s$, $\delta=+59°\ 25'.9$. The track of the meteor begins on the star plate at $\alpha=+2^h\ 23^m 48^s$, $\delta=+59°\ 0'.0$; its brightness increases a little up to the point at $\alpha=2^h\ 18^m\ 17^s$, $\delta=+59°\ 4'.6$, then decreases slightly to the point at $\alpha=2^h\ 17^m\ 0^s$, $\delta=+59°\ 5'.5$. A sudden and marked increase in brightness is noticed at $\alpha=2^h\ 14^m\ 22^s$, $\delta=+59°\ 7'.5$, which is then retained almost to the end ($\alpha=2^h\ 8^m\ 58^s$, $\delta=+59°\ 10'.2$). Only a single line is seen in the spectrum up to the position of the increase in brightness, but from here onward other faint lines appear, no trace of a continuous spectrum being noted, however. The inclination of the track of the meteor to the direction of the stellar spectra is about 75°.

The emission spectra of the two meteors are entirely different from each other.

A procedure entirely rigorous in principle can be employed for determining the wave-lengths of these spectral lines, inasmuch as in both cases the path of each meteor among the stars is known as well as its spectrum. The simple idea on which the process must be based is the following: We must determine a relation between the co-ordinates of suitable stars on the stellar plate and the co-ordinates of the position of a definite spectral line, for instance $H\gamma$, in the spectra of the same star on the spectral plate. From the co-ordinates of the separate points of the track of the meteor on the stellar plate, the co-ordinates of the corresponding points on the spectral plate may be derived and consequently the position of the wave-length in question, i. e., λ 4340.5, can be determined in the spectrum of the

meteor. If the same procedure is carried out for two other wave-lengths, we shall get the positions of three lines of known wave-length in the spectrum of the meteor, whence by means of Hartmann's formula we may derive the wave-lengths of the other lines present in the spectrum.

In the practical execution of this idea, however, we encounter several difficulties. In the first place, the spectral image of the sky is largely distorted by the action of the prism; secondly, an error occurs in the determination of the path of the meteor among the stars on the stellar plate from the fact that the distribution of brightness is not the same in the spectrum of the meteor as in the spectra of the stars, whence the chromatic differences of focus of the objective come in evidence, particularly when the track of the meteor is not very close to the optical axis, as is here the case. The amount of the second error cannot be computed without a knowledge of the spectrum of the meteor and without precise data as to the design of the objective. The effect of the prism involves an inconvenient computation and is not very important without a knowledge of the second error. I therefore decided not to take these errors into account in advance, and I treated the plates in the following manner.

The Troughton measuring machine, with which all the measurements were made, has two scales, A and B, perpendicular to each other. The spectral plate was so oriented under the machine that the direction of the stellar spectra was parallel to scale A, and then, on the one hand, the readings A were made for all lines visible in the spectrum of the meteor for different values of B; on the other hand, the readings A and B were made for the hydrogen lines in the spectra of those stars which fell alongside the spectrum of the meteor and not too far from it. These showed that the dispersion is practically the same at different points of the spectrum of the meteor. Then the relation between the co-ordinates A and B of the different points of the brightest line (in the second case the longest line) would be expressed by an equation of the form:

$$A'=A_0+\alpha(B-B_0)+\beta(B-B_0)^2\ .$$

The co-ordinates computed by this formula pertaining to the different values of B, are probably more accurate than those read

off directly in the measuring machine. Corresponding values of A' were computed for the co-ordinates B, for which the co-ordinates A of the fainter spectral lines were found by measurement; the direct values A of the fainter lines were then compared with these computed values A', and from the differences thus obtained mean values were formed for each line, and thus the definitive distances of all the spectral lines from the brightest line were obtained.

The co-ordinates of the hydrogen lines of the stellar spectra were treated in a similar manner. The reduction of the A co-ordinates of all the hydrogen lines for each star to a selected star was deduced by forming the mean of the separate differences of the separate lines of the two stars; after reducing all the stellar spectra measured to the spectrum of the selected star, the mean values were taken from the co-ordinates obtained for each line, and thus definitive co-ordinates for the hydrogen lines were obtained for this star; by applying the reductions mentioned to these co-ordinates, definitive A co-ordinates were formed for the hydrogen lines of the other stars.

The stellar plate with the track of the meteor was oriented in the measuring machine as nearly as possible in the same way as the spectral plate had been, and the A and B co-ordinates were obtained for the same stars and for a number of points in the meteor's track; the co-ordinates of the track of the meteor were adjusted by means of the formula:

$$A' = A_\circ + \alpha'(B - B_\circ) + \beta'(B - B_\circ)^2 .$$

The ratio of the scales of the two plates was computed from the differences of the co-ordinates of the stars on the stellar and spectral plate (particularly the B co-ordinates); that is, the coefficient was obtained by which the differences of co-ordinates of the one plate must be multiplied in order to obtain the corresponding differences of co-ordinates of the other plate.

Finally the difference of the A co-ordinate of the star and the A' co-ordinate of the point in the meteor track for the same B co-ordinate at which it was measured in the case of the stars, was determined for each star; it was then multiplied with the above-mentioned coefficient and added to the definitive A co-ordinates of the hydrogen lines of this star on the spectral plate. In this way was accomplished what we may call the transfer of the hydrogen spectrum on to the

spectrum of the meteor. I formed the mean of all A differences between a hydrogen line and the brightest lines of the meteor spectrum (in the second case the longest line), and the distribution of the hydrogen wave-lengths thus obtained among the spectral lines of the meteor was made the basis of further computations.

In order to increase the strength of the fainter lines of the meteor spectrum and to diminish the effect of the errors of setting and the errors of the machine, I made an enlarged positive from the original negative of the meteor spectrum, and from this a second negative by contact. It was on this negative that I made the measurements.

From this description of the method employed it may be seen that the principal error affecting the determination of wave-lengths depends on the fact that the transfer of the hydrogen spectrum to the spectrum of the meteor cannot be perfect. In order to improve the wave-lengths of the meteor spectrum thus found, the spectrum must, so to speak, be displaced on its scale; or what is the same thing, the corrections must be added to the separate wave-lengths, which are inversely proportional to the dispersion at the positions in the spectrum in question. The value of the corresponding proportional factor, however, cannot be determined until we are able to identify a number of lines of the meteor spectrum with the spectral lines of some terrestrial element.

METEOR OF MAY 11, 1904

TABLE I

Inches	$\mu\mu$	$\mu\mu$		$\mu\mu$	$\mu\mu$	
2.24788	357.82		218	−0.52	357.30	3 weak
2.27710	364.40		233	−0.55	363.85	4
2.31988	374.90		258	−0.62	374.28	4 double
$H\theta$ 2.33839	379.80					
$H\eta$ 2.35215	383.59					
2.35437	384.22		282	−0.67	383.55	3
2.36201	386.40		288	−0.69	385.71	3
$H\zeta$ 2.37040	388.84					
2.38781	394.08	−0.70	308	−0.73	393.35	10
$H\epsilon$ 2.39730	397.05					
2.39915	397.63	−0.77	318	−0.76	396.87	5
2.42175	405.06		339	−0.81	404.25	2 double
$H\delta$ 2.43652	410.18					
2.44801	414.31		366	−0.87	413.44	1 double
2.47262	423.66	−0.96	394	−0.94	422.72	1 sharp
$H\gamma$ 2.49796	434.07					

The table contains in the first column the A co-ordinates in English inches of the lines of the meteor spectrum and of the hydrogen lines. The last decimals are merely the results of computation. The last column gives relative brightness and remarks as to the appearance of the lines. In deriving the Hartmann formula I assumed the following wave-lengths for the hydrogen lines, after Evershed:[1]

$$H\theta-379.80,\quad H\eta-383.55,\quad H\zeta-388.92,$$
$$379.80\qquad 383.59\qquad 388.84$$
$$H\epsilon-397.00,\quad H\delta-410.20,\quad H\gamma-434.05$$
$$397.05\qquad 410.18\qquad 434.06.$$

The second line of values was obtained by the formula:

$$\lambda=167.48+\frac{[2.22130]}{3.12238-A}.$$

The corresponding wave-lengths of the spectrum of the meteor are given in the second column of the table.

There can be scarcely any doubt that the two brightest lines are the calcium lines H and K of the solar spectrum, for the small and surely trustworthy corrections of -0.77 and $-0.70\ \mu\mu$ suffice for reducing the computed wave-lengths to the wave-lengths of those lines (396.86, 393.38). The line 423.66 similarly belongs to the calcium spectrum; the relative intensity of this line as compared with H and K is known to be very dependent on the conditions under which the calcium vapor is brought to luminosity; the computed wave-length required a correction of $-0.97\ \mu\mu$.

The fourth column gives $\frac{d\lambda}{dA}$. From the corrections of the three calcium lines the displacement of the meteor spectrum on its scale comes out -0.00238 inches (mean of -0.00227, -0.00242, -0.00246); the corresponding corrections of the remaining wave-lengths are given in the fifth column, and definitive wave-lengths in the sixth column.

As to the identification of the remaining lines, the means at my disposal, consisting of the *Atlas der Emissionsspectren* by A. Hagenbach and H. Konen, and the *Wellenlängen Tabellen* by F. Exner and E. Haschek, enabled me to determine the following points:

[1] *Memoirs of the Royal Astronomical Society*, 54, Appendix V.

The wave-length 383.55 corresponds to the *Mg* lines 382.95, 383.25, 383.84, which are the brightest magnesium lines in the portion of spectrum photographed.

λ 404.25 $\mu\mu$ represents the double potassium line 404.43 and 404.75, which is similarly the brightest *K* line in this part of the spectrum.

METEOR OF AUGUST 12, 1904

The spectrum of this meteor lies farther from the center of the plate than is the case of the earlier meteor, so that the measurements, particularly those of the hydrogen lines in the stellar spectra, are more uncertain.

TABLE II

Inches	$\mu\mu$	$\mu\mu$	$\mu\mu$	$\mu\mu$	
1.98752	376.11	+1.48	+1.37	377.48	2
2.00553	377.69		+1.34	379.03	2
2.02020	378.99		+1.30	380.29	2
2.03968	380.74	+1.24	+1.27	382.01	1
$H\eta$ 2.06923	383.46				
2.07550	384.04		+1.21	385.25	1 a line?
2.11644	387.91	+0.97	+1.15	389.06	10 long
$H\zeta$ 2.12810	389.08				
2.14136	390.39		+1.12	391.51	2 double?
2.16531	392.79		+1.08	393.87	1
2.19044	395.37	+1.12	+1.06	396.43	1 a line?
$H\epsilon$ 2.20729	397.12				
2.21754	398.22		+1.04	399.26	5
2.24963	401.68	+0.95	+1.02	402.70	3
2.28516	405.64		+1.01	406.65	1 a line?
$H\delta$ 2.32431	410.16				
2.33170	411.03	+1.07	+1.00	412.03	1 diffuse
$H\gamma$ 2.50794	433.89				

The first column again gives the *A* co-ordinates, and the last column gives the relative brightness and remarks. The second contains the wave-lengths computed by the formula

$$\lambda = 168.44 + \frac{[2.69698]}{4.37865 - A}.$$

We see that the hydrogen wave-lengths are represented less satisfactorily than in the first case, whence we may expect that the corrections of the wave-lengths in the spectrum of the meteor will be larger than for the first meteor. The comparison of the meteor

spectrum with the spectra of terrestrial elements indicated that the wave-lengths

380.74, 387.91, 395.37, 401.68, 411.03

lie close to the positions in the spectrum of the brightest lines of helium and also so nearly match their relative brightness that there can be no doubt of the presence of this element in the meteor. In the *Astrophysical Journal* (**3**, 9, 10, 1896) Messrs. Runge and Paschen give for these lines the following wave-lengths and relative intensities:

381.98 (4), 388.88 (10), 396.49 (4), 402.63 (5), 412.10 (3).

The corrections required for the computed wave-lengths are given in the third column.

The pure-green color of the meteor doubtless indicates that the wave-length 376.11 corresponds to the thallium line at 377.59 which is the brightest in this portion of the spectrum. The corrections found for six wave-lengths ought to be treated in the same way as for the meteor of May 11, but they show again that the measurements, particularly in the hydrogen lines in the stellar spectra (which determine the scale of the spectrum), are here insufficiently precise, inasmuch as the progression of the corrections is reversed from that which corresponds to the displacement of the spectrum on its scale. I therefore drew an interpolation curve, based upon the corrections given, and took from it the corrections to the computed wave-lengths; these corrections are given in the fourth column, while the fifth contains the definitive wave-lengths. I was unable to certainly identify any other line with any line of a terrestrial element.

OBSERVATORY, MOSCOW
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ON THE QUANTITATIVE SPECTRA OF CERTAIN ELEMENTS[1]

By JAMES H. POLLOK and A. G. G. LEONARD

INTRODUCTION

The following quantitative spectra of iron, aluminium, chromium, silicon, zinc, manganese, nickel, and cobalt, are, with slight modifications, taken after the manner devised by Professor W. N. Hartley, as published in the *Philosophical Transactions of the Royal Society* in 1884, **175**, 49–62, 325–342.

For analytical purposes a knowledge of the residuary lines of spectra is of the greatest assistance, as on diluting a solution of a salt, the lines of the spark-spectrum disappear so rapidly, that with 0.1 per cent. solutions, the spectrum is difficult to identify by reference to an index where all the lines of the element are carefully recorded, especially as the last lines that disappear are not necessarily the most intense. On a plate giving the spark-spectrum of some chloride of beryllium, let us say, one might very well have a few foreign lines closely agreeing with lines of iron, manganese, or titanium, and without very exact measurement, it might be impossible to decide to which they belonged; but on the other hand, if we knew that these lines were the residuary lines of titanium, and that the residuary lines of iron and manganese were quite different, we should know definitely that a trace of titanium was present, and not iron or manganese. Again, if we know that the residuary lines of an element are absent, we know at once that the element is absent, so that it is only necessary to look for the residuary lines. Hartley investigated the dilution spectra of a large number of elements; but with the exception of aluminium, silicon, and zinc, the above are not among them, and as the authors are engaged in an investigation of the methods of separating the elements of the cerium and yttrium groups, they find that a knowledge of the residuary lines of all the common elements of the ammonia and ammonium sulphide groups is necessary. Gold electrodes have been substituted for graphite to bring

[1] Extract from *Scientific Proceedings of the Royal Dublin Society*, 11, Nos. 17 and 18, July 1907.

the spectra into uniformity with other work by the authors, and in particular to make them readily comparable with the general index of spectra published by one of the authors in the *Proceedings* of this society. On comparison of the dilution spectra of zinc and silicon with those of Hartley, it would seem that gold electrodes are not so sensitive as graphite. The results are otherwise substantially the same, a few more lines having been observed with a 1 per cent. solution of zinc, and all the lines disappear more rapidly; the last lines to disappear on dilution are identical with those observed by Hartley. That graphite should be more delicate than gold appears very natural, as the graphite tends to absorb the solution-sparks over a larger surface, and hence yields more vapor of the element under examination; but for all ordinary analytical purposes, gold is more convenient.

The work was done with a one-prism quartz spectrograph, by Hilger, using the spark produced by a Ruhmkorff's coil and condenser, with a Hemsalech self-induction coil placed in the circuit for the removal of air-lines. The plates were "Rainbow Fast," made by the Warwick Photo Co., and in every case the exposure was 1 minute; this photographed clearly from λ 4792.8 to λ 2544 on one plate. To go farther down in the ultra-violet, it would be necessary to readjust the instrument and take another set of photographs.

The general method of procedure was to make a strong or saturated solution of the chloride of the element under consideration; also solutions containing one gram of the element in every 100, 1000, 10,000, 100,000 parts of solution. A photograph was taken of the gold electrodes with a long slit; the slit was then shortened and the metal sparked, thus giving the spectrum of gold with long lines, and the spectrum of the metal with short lines. The process was then reversed, the metal taken long, and the gold short, so that any lines coincident with gold lines might be seen. A photograph was taken then with both the strong solution and gold electrodes long, and the metals short, to show any lines developed by the metals, but not by their solutions. Then in every case the last four spectra taken gave the gold electrodes long, with short lines between, of the spark spectra of solutions containing 1 per cent., 0.1 per cent., 0.01 per cent., 0.001 per cent. of the element under examination.

To distinguish briefly between the different phases of the lines with diminishing concentration, use has been made of some of the letters of the Greek alphabet, with the following meanings:

τ=	seen with the metal, but not with strong solutions.							
σ=	"	"	strong solutions, but not with 1% solutions.					
ϕ=	"	"	1%	"	"	"	" 0.1%	"
χ=	"	"	0.1%	"	"	"	" 0.01%	"
ψ=	"	"	0.01%	"	"	"	" 0.001%	"
ω=	"	"	0.001%	"				

No new measurements were attempted, the lines being identified by means of a finely graduated ivory scale, and the corresponding published lines tabulated. In the case of manganese, however, one of the residuary lines, λ 2594.0, was not found in the tables at our disposal, and our own measurement is given.

In the case of cobalt the solution was not diluted so abruptly, and this shows the gradual extinction of the lines with diminishing concentration better than the others; but as the whole object was to find the residuary lines, one passes directly from a saturated solution to a solution containing only 1 per cent. of the element under examination, and then dilutes until the lines entirely disappear. In the case of chromium, silicon, manganese, and zinc, all the dilutions are not given in the plates,[1] as lines that can still be seen on the negatives cannot be seen in the reproductions at all, as will be obvious by comparing the tables with the plates. Even with 1 per cent. solutions, the lines do not come out by any means strongly with one minute's exposure, and with 0.1 per cent. they are always very faint, and very few substances give lines that will show at all with 0.001 per cent.

GOLD ELECTRODES

To facilitate the identification of the lines, some of the strong gold lines have been numbered, from 10 to 25, and their wavelengths are given in the Table I; and in the subsequent tables these numbers are inserted in their proper place. Thus in the case of chromium, we see from the table that the first triplet of persistency ψ lies between 11 and 12, and we know where to look for it on the plate.

[1] The author's plates are omitted here.

TABLE I

Numbered Gold Lines

No.	Wave-Length	No.	Wave-Length
9..........	4792.8	18..........	3029.3
10..........	4488.4	19..........	2913.6
11..........	4315.4	20..........	2825.6
12..........	4065.2	21..........	2748.3
13..........	3898.0	22..........	2676.1
14..........	3586.5	23..........	2641.6
15..........	3383.0	24..........	2590.2
16..........	3280.8	25..........	2544.3
17..........	3122.9		

IRON

The progressive disappearance of the lines of dilute solutions is given in the following table; but there are so many φ lines that it

TABLE II

Quantitative Spectrum of Iron Chloride

Wave-length	Intensity and Persistency	Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
10		3618.9	10 φ	2692.7	6 φ
4415.3	8 σ	3610.3	4 φ	22	
4404.9	10 σ	3609.0	9 φ	2684.8	6 φ
4383.7	10 φ	14		2666.7	7 φ
4325.9	10 σ	3581.3	10 χ	2664.7	7 φ
11		3570.3	8 χ	2631.4	4 ψ
4308.0	10 σ	3565.5	8 χ	2628.4	8 ψ
4271.9	10 σ	3490.7	6 φ	2625.8	7 ψ
4260.7	10 σ	3475.6	7 χ	2621.7	6 χ
4250.9	8 σ	3466.0	7 χ	2617.7	7 χ
4071.9	10 σ	3441.1	7 χ	2613.9	9 χ
12		15–18		2612.0	9 χ
4046.0	10 σ	3021.2	2 ψ	2607.2	9 χ
4005.3	8 σ	3020.8	2 ψ	2599.5	10 ψ
13		2973.4	2 χ	2598.5	9 ψ
3860.1	9 σ	2970.2	2 χ	2586.0	8 χ
3828.0	9 σ	2967.0	2 χ	2567.0	4 χ
3816.0	9 σ	2965.4	1 χ	2562.0	6 ψ
3767.3	7 φ	19–20		2549.7	4 χ
3758.4	8 φ	2783.8	7 φ	25	
3749.6	10 φ	2779.3	5 φ	2539.0	5 χ
3745.7	7 φ	2767.6	7 ψ	2533.9	7 χ
3737.3	8 ψ	2755.8	10 ψ	2529.6	6 φ
3735.0	10 ψ	2747.1	7 φ	2526.3	6 φ
3722.7	6 ψ	2743.2	8 χ	2525.5	7 φ
3720.1	8 ψ	21		2522.9	6 χ
3687.6	6 φ	2739.6	10 ψ	2511.8	7 χ
3648.0	9 φ	2727.6	8 χ		
3631.6	10 φ	2714.5	7 χ		

was not thought necessary to record more than the strongest. Some of the lines that show well with a strong solution, but are not seen with dilute solutions, are marked σ.

ALUMINIUM

There is a strong aluminium line at λ 3587.0, practically coincident with gold line No. 14 (λ 3586.5), and in consequence it cannot be followed in the dilution spectra. Quite a number of lines show strongly with the metal, but only very faintly, or not at all, with solutions. Of those the following belong to aluminium:

4663.1	10 τ	3064.4	8 τ
4530.5	6 τ	3057.3	8 τ
4511.9	6 τ	3054.8	8 τ
4479.4	6 τ	3050.2	8 τ
3066.3	8 τ		

The rest between gold lines 22 and 24 belong to iron, and come from the small traces of iron in metallic aluminium, and they correspond with the most persistent lines of the iron solutions.

TABLE III

QUANTITATIVE SPECTRUM OF ALUMINIUM CHLORIDE

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
3961.7	9 ω	2816.4	10 χ
3944.2	9 ω	21–22	
13		2660.5	5 ϕ
3587.0	10 ϕ	2652.6	5 ϕ
14–17		23–24	
3092.8	9 ψ	2575.5	7 ϕ
3082.3	9 ψ	2568.1	7 ϕ
18–20		25	

CHROMIUM

We photographed the lines of an alloy of 50 per cent. chromium and 50 per cent. iron short, with gold and iron lines long, the iron lines of the long spectrum thus canceling the iron lines in the short, and showing only the chromium lines short. This plan was adopted owing to the difficulty of procuring or making chromium free of iron.

TABLE IV

QUANTITATIVE SPECTRUM OF CHROMIUM CHLORIDE

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
11		2988.8	8 ϕ
4289.9	10 ψ	2980.9	8 ϕ
4274.9	10 ψ	2971.9	8 ϕ
4254.5	10 ψ	2953.4	8 ϕ
12–13		19	
3605.5	10 χ	2843.3	10 ψ
3593.6	10 χ	2835.2	10 ψ
14		2830.5	10 ψ
3578.8	10 χ	20	
3430.5	10 ϕ	2766.6	8 ϕ
3422.9	10 ϕ	2762.7	8 ϕ
3421.4	10 ϕ	21	
3408.9	10 ϕ	2698.8	8 ϕ
3403.5	10 ϕ	22	
15–16		2663.6	8 ϕ
3180.8	10 ϕ	2659.0	8 ϕ
3132.2	10 ϕ	2653.6	8 ϕ
17		23	
3050.9	8 ϕ		
3030.4	Group ϕ		
18			
3015.3			

SILICON

The lines of silicon do not develop in acid solutions, and quite large quantities may be present in acid solutions of other elements without giving any indication of their presence when sparked; so that for the detection of silicon, it is absolutely essential to spark an alkaline solution. The group a little beyond gold line No. 25 is very characteristic, and easily recognized.

TABLE V

QUANTITATIVE SPECTRUM OF SILICATE OF SODA

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
4131.0	4 ϕ	24–25	
4128.2	4 ϕ	2528.6	8 ψ
12		2524.2	6 ϕ
3905.8	5 ϕ	2519.3	8 ϕ
13		2516.2	10 ψ
2881.7	10 ϕ	2514.4	7 ϕ
20–23		2507.0	8 ϕ
2631.4	8 ϕ		

ZINC

Zinc has a strong line coincident with gold line No. 16, and another with the gold line just beyond No. 20. As in the case of aluminium, quite a number of lines develop strongly with the metal and strong solutions, but not with dilute solutions; these are marked σ in the following table:

TABLE VI

Quantitative Spectrum of Zinc Chloride

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
8		18	
4810.7	10 ϕ	3018.5	4 σ
9		19–20	
4722.3	10 ϕ	2801.0	8 ϕ
4680.4	10 ϕ	2771.0	8 ϕ
10–15		2756.5	6 ϕ
3345.3	10 χ	21	
3303.0	10 χ	2712.6	2 σ
3282.4	10 χ	2684.3	2 σ
16–17		22–24	
3076.0	8 σ	2582.6	2 σ
3072.2	10 σ	2570.0	2 σ
3035.9	8 σ	2558.0	10 χ

TABLE VII

Quantitative Spectrum of Manganese Chloride

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
4823.7	8 σ	3460.5	10 ϕ
9		3442.1	10 ϕ
4783.6	6 σ	15–18	
10–11		2949.3	10 χ
4083.8	6 σ	2939.4	8 χ
12		2933.1	8 χ
4055.7	6 σ	19	
4048.9	6 σ	2879.5	6 ϕ
4041.5	6 σ	20–21	
4035.9	6 σ	2705.7	6 ϕ
4034.6	6 σ	22	
4033.2	6 σ	2701.7	6 ϕ
4030.9	8 χ	23	
13		2639.9	6 ϕ
3823.6	6 ϕ	2632.5	6 ϕ
3806.9	10 ϕ	2625.7	6 ϕ
14		2618.2	6 ϕ
3496.0	8 ϕ	2605.8	10 ω
3488.8	10 ϕ	2594.0	10 ω
3483.0	10 ϕ	24	
3474.2	10 ϕ	2576.2	10 ω

MANGANESE

The spectrum given by the metal is practically identical with that of a strong solution. The three ω lines in the region of gold line No. 24 form a very characteristic group, by which this element can be rapidly identified. The general results are as shown in Table VII.

NICKEL

The plates show that the same lines are developed by the metal and strong solutions; the relative rate of disappearance of the lines on dilution is shown in the table:

TABLE VIII

Quantitative Spectrum of Nickel Chloride

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
3619.5	10 ϕ	3134.3	8 χ
3597.8	10 ϕ	17	
14		3102.0	8 χ
3566.5	10 ϕ	3101.6	8 χ
3524.6	10 χ	3064.7	7 ϕ
3515.2	10 χ	3057.7	8 ψ
3510.5	10 χ	3054.4	7 ψ
3493.1	10 χ	3050.9	8 ψ
3472.7	8 ϕ	3038.0	7 χ
3446.3	8 χ	18	
3433.7	7 χ	3012.1	8 χ
3423.8	7 ϕ	3003.7	8 χ
3414.9	8 ψ	19–23	
3393.1	7 ϕ	2546.0	7 ϕ
15		24–25	
3247.7	7 ϕ	2510.9	8 ψ
3233.1	8 ϕ		

COBALT

Like iron, manganese, and nickel, cobalt gives the same lines with the metal and strong solutions. The results of dilution are given in Table IX.

After sparking the strong solutions, it was found that in many cases the electrodes alone gave quite strong spectra of the metal under examination, and at first it was supposed that the solutions had sprayed on to the fresh electrodes; but on keeping the fresh electrodes in another room, no difference was observed, and in the case of an element such as iron or calcium, the dilution spectra could not be

TABLE IX

QUANTITATIVE SPECTRUM OF COBALT CHLORIDE

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
4531.1	4 σ	3412.8	7 ϕ
10		3405.3	8 ψ
4469.7	1 σ	15–17	
4121.5	8 ϕ	3086.9	6 ϕ
4118.9	8 σ	3072.5	6 ϕ
12		18–21	
3995.5	8 ϕ	2694.7	8 ω
13		22	
3894.2	10 ψ	2663.6	8 χ
3873.2	10 ψ	23–24	
3845.6	10 ϕ	2587.2	8 ϕ
14		2582.3	8 χ
3502.4	8 χ	2580.4	8 ψ
3489.5	10 ϕ	2564.2	8 ϕ
3474.1	10 χ	2559.5	8 χ
3465.9	8 ϕ	25	
3453.6	8 ψ	2528.7	7 χ
3449.6	7 ϕ	2525.1	7 χ
3443.8	7 ϕ	2519.0	8 ω
3433.2	7 ϕ		

followed beyond the 0.1 per cent. solution, as the electrodes then gave as strong spectra as the solutions. It was then seen that the atmosphere was charged with the element, and remained charged for a considerable time. In the following investigations the difficulty was got over by beginning with the most dilute solution, and working backward toward the strong solutions, finally sparking the metal when it could be procured.

The photographs of spectra extend from λ 5900 to λ 2500; but the plates were not very sensitive below λ 4792.8, nor was the instrument in perfect focus beyond λ 2590.2.

It is a remarkable fact that the residuary lines of an element differ greatly with the method of excitation, and there is no guarantee that the residuary lines here tabulated would be the most persistent lines if the substances were vaporized by something other than the condensed spark; certainly, in the case of the oxyhydrogen flame, there is a notable difference; thus, with manganese, we have shown that, when the condensed spark is used, the residuary lines are λλ 2605.8, 2594.0, and 2576.2; but if the oxyhydrogen flame be employed to vaporize the element or its compounds, the residuary lines, as

shown by Professor Hartley,[1] are λλ 4034.6, 4033.2, 4030.9; and in general, we note that, with the oxyhydrogen flame, the residuary lines tend to the less refrangible end of the spectrum; but with the condensed spark they tend to the more refrangible end. Apparently the nature of the dilutant has no effect on the residuary lines; thus the same residuary lines would be obtained whether the metal was in the form of a dilute solution or alloyed with another metal; but we have not yet investigated whether the degree of persistency is affected; probably it would be influenced by the relative volatility of the diluting metal in the alloy, and the sensitiveness greatly reduced owing to the vapor of the dilutant being itself a conductor, so that in an alloy one would not readily detect the presence of less than 0.1 per cent. of a substance. In tabulating the results, when the intensities were other than those usually accepted, they are inclosed in brackets.

BARIUM

The salt used was barium chloride; and the most persistent lines were situated in the visible part of the spectrum, the residuary lines being λλ 4554.2, 4130.9. As metallic barium is not easily procured in a state of purity, we were unable to determine whether any lines are developed by the metal, but not by solutions.

TABLE X

Quantitative Spectrum of Barium Chloride

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
5535.7	10 ϕ	4283.3	8 σ
5519.4	4 ϕ	4166.2	10 ϕ
5524.8	6 σ	4130.9	10 ω
4934.2	10 ψ	[No. 12,	Gold.]
4900.1	[8] σ	3993.6	8 σ
[No. 9,	Gold.]	3910.1	6 σ
4726.6	[3] σ	[No. 13,	Gold.]
4691.7	[3] σ	3892.0	10 ψ
4673.7	[3] σ	[No. 14,	Silver.]
4554.2	10 ω	3501.3	8 σ
4525.2	10 χ	[No. 15,	Silver.]
4506.1	6 σ	3357.0	[4] σ
[No. 10,	Gold.]	[No. 20,	Gold.]
4432.1	8 σ	2771.5	8 ϕ
4402.7	8 σ	[No. 23,	Gold.]
4350.5	6 σ	2634.9	8 ϕ
[No. 11,	Gold.]		

[1] *Phil. Trans.*, 185, Part I, 161–212, 1894.

STRONTIUM

Strontium chloride was the salt used. The most persistent lines were situated in the visible part of the spectrum, residuary lines λλ 4607.5, 4305.6, 4215.7, and 4077.9 being faintly seen with a dilution of $\frac{1}{1000000}$. As in the case of barium, we were unable to test the difference between the spark-spectrum of the metal and a strong solution.

TABLE XI

QUANTITATIVE SPECTRUM OF STRONTIUM CHLORIDE

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
5535.0	8 σ	4607.5	10 ω
5522.0	8 σ	[No. 11,	Gold.]
5504.5	8 σ	4305.6	30 ω
5486.4 }	6 }	4215.7	100 ω
5481.1 }	10 } φ	4162.0	20 φ
5451.1	5 σ	4077.9	100 ω
5257.1	8 σ	[No. 12,	Gold.]
4962.4	8 φ	4032.5	[4] σ
4876.3	6 σ	[No. 13,	Gold.]
4832.2	6 σ	3475.0	20 φ
4812.0	6 σ	3464.6	100 φ
[No. 9,	Gold.]	[No. 15,	Silver.]
4742.1	6 σ	3380.9	80 σ
4722.4	6 σ	3351.3	3 χ

CALCIUM

Calcium chloride was the salt used; and, as in the case of barium and strontium, the most persistent lines were situated in the visible part of the spectrum, the residuary lines being λλ 4226.9, 3968.6, and 3933.8. On taking the spark-spectrum of the metal, it was found to contain magnesium, manganese, and silicon; but in addition to the residuary lines of these elements, which are all situated in the ultra-violet part of the spectrum above gold line No. 18, the metal showed one or two very well-defined and intense lines that are either not shown at all by strong solutions, or only faintly shown: those lines are marked τ in the table. The dilution-spectrum of calcium was investigated by Sir William and Lady Huggins in a manner differing somewhat in detail from that adopted in the present experiments; but the conclusions are the same as regards the identity of the residuary lines.

TABLE XII

QUANTITATIVE SPECTRUM OF CALCIUM CHLORIDE

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
5594.6	8 σ	4289.5	8 φ
5270.5	8 σ	4283.2	8 φ
4878.3	6 σ	4226.9	10 ω
[No. 9,	Gold.]	[No. 12,	Gold.]
4586.1	4 σ	3968.6	80 ω
4581.7	4 σ	3933.8	100 ω
4527.2	[4] σ	[No. 13,	Gold.]
4455.0	10 φ	3737.2	15 ψ
4435.1	10 φ	3706.2	10 ψ
4425.6	10 φ	3644.5	2 φ
4318.8	8	3630.8	1 φ
[No. 11,	Gold.]	[No. 14,	Silver.]
4307.9	6 σ	3179.4	10 χ
4302.7	10 σ	3159.1	10 χ
4299.1	6 σ	[No. 17,	Gold.]

MAGNESIUM

Magnesium chloride was the salt used. Unlike barium, strontium, and calcium, the most persistent lines are situated in the ultra-violet part of the spectrum, the residuary lines being λλ 2852.2, 2798.2, and 2790.9.

TABLE XIII

QUANTITATIVE SPECTRUM OF MAGNESIUM CHLORIDE

Wave-Length	Intensity and Persistency	Wave-Length	Intensity and Persistency
5528.7	6 φ	[No. 17,	Gold.]
5183.8	10 φ	3097.1	[8] φ
5167.6	8 φ	3093.1	[8] φ
[No. 9,	Gold.]	[No. 18,	Gold.]
4703.3	[8] τ	2937.0	10 χ
[No. 10,	Gold.]	2928.7	10 χ
4481.3	10 σ	2915.5	10 σ
4352.2	[8] τ	2852.2	10 ω
[No. 13,	Gold.]	[No. 20,	Gold.]
3838.4	10 σ	2798.2	8 ω
3832.5	10 σ	2790.9	10 ω
3829.5	10 σ	2783.1	4 φ
[No. 15,	Silver.]	2781.5	4 φ
3336.8	8 σ	2779.9	6 χ
3332.3	8 σ	2778.4	4 φ
3330.1	6 σ	2776.8	4 φ

The metal gives one or two strong lines that are not seen, or only very faintly seen, with strong solutions. Those lines are marked τ.

The quantitative spectrum of magnesium was previously investigated by Professor W. N. Hartley, and his results are in accordance with the present observations; but as previously explained, Professor Hartley's method of observation gave a greater quantity of vapor, and an apparently greater persistency of the lines; but the relative persistencies are substantially the same, and the residuary lines are identical.

POTASSIUM

Photographs were taken with metallic potassium in an atmosphere of hydrogen, and also with solutions of potassium chloride.

Potassium is characterized by a very feeble spark-spectrum, only two lines showing with one minute's exposure either with the metal or a saturated solution; and with a 1 per cent. solution they are scarcely visible. It is remarkable that the flame-spectrum is very intense; apparently the temperature of the oxyhydrogen flame, or even the Bunsen, gives a far more brilliant spectrum than the condensed spark. This is, no doubt, owing to the greater quantity of vapor produced.

TABLE XIV

Quantitative Spectrum of Potassium Chloride

Wave-Length	Intensity and Persistency
4047·4	10 ϕ
4044·3	10 ϕ
3447·5	(8) σ
3446·5	(8) σ

SODIUM

Sodium chloride was used for the solutions, and the metal was photographed in an atmosphere of hydrogen. Sodium gives a well-marked spectrum of three pairs of lines; but, with the exception of the D lines, they are not very persistent; and, as in the case of potassium, the sodium lines do not show with the spark nearly so strongly as with the oxyhydrogen flame, or even the Bunsen burner.

It is also very remarkable that the D lines do not seem to show as strongly with the metal as with a strong solution of the chloride.

TABLE XV

Quantitative Spectrum of Sodium Chloride

Wave-Length	Intensity and Persistency
5896.2	10 ω
5890.2	10 ω
5688.3	6 ψ
5682.9	6 ψ
3303.1	10 χ
3302.5	10 χ
2852.9	(6) σ

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ON SOME DEVICES FACILITATING THE STUDY OF SPECTRA[1]

By WALTER NOEL HARTLEY

It has been shown in previous communications that flame-spectra at high temperatures have a special value, inasmuch as minute traces of metallic and mineral substances may be readily detected, and their spectra photographed; for instance, from iron ores and pig-iron as many as ninety lines of the element are photographed at one exposure.[2]

The source of heat being the oxyhydrogen flame, the temperature lies between 1400° and 2000°; and as 1775° is about the melting-point of platinum, some other support than that metal must be used for solid substances. Thin slips of Donegal cyanite and ashless filter-papers have been used almost exclusively, and their use described in the publications quoted. The cyanite consists of 98.0 per cent. of aluminium silicate, according to an unpublished analysis made in my laboratory; it merely softens in the flame, and it is useful for long exposures of half an hour or upward. The lines of sodium and lithium in the yellow and red are the only impurities which are photographed. The filter-papers are useful for rapid exposures of one to two minutes; they yield the sodium line only; but atmospheric dust settles upon them, and consequently feeble red and green bands of calcium sometimes appear, especially when ten filter-papers are used for one spectrum. Cyanite is not always procurable, but carborundum is now an article of commerce.

Carborundum.—This gives no spectrum in the oxyhydrogen flame; it is incombustible, and quite infusible. This material in a form adapted for supports is manufactured by the Carborundum Company for other purposes, the small crystals being mixed with porcelain clay, and fired at a high temperature. Thin, flattened

[1] *Scientific Proceedings of the Royal Dublin Society*, 11, No. 19, August 1907.

[2] W. N. Hartley, "Flame-Spectra at High Temperatures," *Phil. Trans.*, *A*, 185, 161–211, 1894.

Hartley and Ramage, "A Simplified Method for the Spectrographic Examination of Minerals," *Chem. Soc. Trans.*, 79, 61, 1901.

pieces, four inches in length and $\frac{1}{16}$ of an inch in thickness, are sold as silversmith's stones. It is advisable that this material be cautiously introduced into the flame.

Quartz fibers and thin rods.—At the melting-point of platinum quartz only softens; hence this material, which is now manufactured by Messrs. Johnson & Mathey, in the form of rod and tube, is available for use. The quartz, as a rule, gives no impurity lines.

The Mecke burner.—In all the various forms of smokeless burners which have been devised, the chief defect lies in the small area of the cross-section of the flame which provides the maximum temperature; great variations in temperature arise from the irregularity of the flame, when subject to the influence of draughts, especially horizontal currents of air. From these defects the Mecke burner is entirely free; and for ordinary spectroscopic purposes I can recommend no other. Its construction is that of a Gifford's injector, the current of gas injecting into the tube the requisite amount of air necessary for its complete combustion. In order to admit of the gas and air being mixed together, two metallic gratings are placed within the tube of the burner; and about half an inch above the upper grating a cap consisting of a third grating is fitted. As the upper part of the tube is choked by the gratings, it is expanded to compensate for this. To ignite the mixture of gas and air, the match-flame must not be held above, but close to the grating. Supposing the diameter of the top of the burner be two centimeters, the gaseous mixture is seen to burn from about thirty-seven little jets, each of which shows a green cone if the air is excessive, but a blue one if the mixture is of the right nature to obtain the highest temperature. The maximum heating effect is from two to three millimeters above the grating; and it is equable across the whole diameter of the tube. Platinum wire of the ordinary thickness just fuses upon the surface. The shape of the flame is a cone about 25 mm high, and therefore pyramidal. Draughts do not affect the flame. In the Mecke burner, fused alkali and alkaline earth-salts are easily examined on platinum wire, hard asbestos fibers, quartz fibers, or on tobacco-pipe. It is, of course, necessary to ascertain what spectrum-lines the support yields, and eliminate the lines or bands from the spectra subsequently observed. Quartz fibers and platinum obviously yield nothing.

Fusible silicates, such as lepidolite, show the spectra of potassium, lithium, and, with a wide slit, even of rubidium. A convenient way of examining solutions is to employ a clay tobacco-pipe, to plug the mouthpiece of the pipe with two or three asbestos fibers, and to pour the solution into the bowl. By inclining the pipe, the solution soaks through the asbestos, the water evaporates, and the salt fuses on the fibers. Similarly, a piece of quartz tube is drawn out to a capillary point, the end being left open; the solution then issues in drops, which dry upon the point of the tube; it is the solid salt, and also spray from the solution, which yields the spectrum. The quartz is unbreakable by the contact of the hot material with a cold solution. When even white-hot, it may be dropped into cold water without cracking, or into hydrochloric acid in order to cleanse it.

The Mecke blast-burner.—This modification, in addition to the injector, has an air-jet placed higher up in the tube. The air-blast must be supplied with a regulated constant-pressure, which may be obtained in any way, as by bellows, a rotary fan, or tromp; but the pressure should not be less than two kilograms per square centimeter. With water direct from the high-pressure mains, the water-blower is satisfactory; but the instrument should be fitted with a pressure-gauge. A blower fitted up twenty-five years ago has been found generally effective. The essential parts are a Körting's jet soldered on to a water-tap, to which again the inlet-tube of the blower is soldered. The air-reservoir is a tube 4 feet long by 3 inches broad. Platinum wire, of the usual thickness suitable for spectroscopy, is easily melted n the flame at its hottest part; and therefore quartz-fibers are a suitable material to use as supports. To convey some idea of the advantages gained by the use of these burners for spectroscopic work, I may mention that the use of fused salts or infusible compounds is to be preferred to aqueous solutions, or to substances strongly acidified with hydrochloric acid. Thus the examination is simplified and made more cleanly in manipulation. Any salt previous to being examined should be heated in a covered porcelain crucible until it ceases to decrepitate or evolve water; it is then in a suitable condition to be placed on the support.

In the practical use of the flame spectra there is no difficulty in recognizing traces of the alkalis by their lines; but with salts of

the alkaline earth-metals, the most characteristic feature of their spectra is bands, and not lines. The usual mode of examination in the Bunsen flame is to moisten the solid substance with hydrochloric acid, to take some of this up on a platinum wire and place it in the flame, when a momentary brilliant flash follows; after a short interval very little of the spectrum remains to be seen, and what there is has an essentially different appearance. It is hardly necessary to point out that volatile metallic chlorides yield the first spectra; and those subsequently visible are the spectra obtained, first by the conversion of the chlorides into oxides, and secondly by the reduction of oxides to the metallic state and the coloration of the flame by the metals.[1]

By employing the high temperature of a Mecke burner even of the simple pattern, the second spectra are rendered constant for a long period, even if the oxides or sulphates are employed. Accordingly what distinguishes the least trace of calcium is a red band and a green band, one on each side of the sodium line. Strontium yields two red bands and one orange band. As a rule, neither the blue line of calcium nor the corresponding blue line of strontium is plainly seen. If any calcium salt be placed in the flame, the effect first seen is a strong sodium spectrum; but the heat is so intense that the sodium is soon volatilized; and nothing but the red coloration of the calcium remains; though this may continue for an hour or longer, and may be photographed. The red and green bands have been obtained from calcium chloride, calcium nitrate, calcium carbonate, calcium sulphate, and from quick-lime. The photograph of the bands taken from calcium nitrate during one hour's exposure in a simple Mecke burner shows the essential features of the calcium spectrum. The slit was sufficiently narrow to divide the two sodium lines when very minute quantities of sodium were present.

A device for showing chloride spectra.—When an oxide is supported in the flame of a Mecke burner, it may be made to yield a chloride spectrum by introducing a few fibers of asbestos or tobacco-pipe upon which is crystallized some ammonium chloride. The effect is, however, evanescent; and to operate continuously over long periods,

[1] W. N. Hartley, "On the Thermo-Chemistry of Flame-Spectra at High Temperatures," *Proc. Roy. Soc., A*, 79, 242–261, 1907.

the burner is supplied with gas mixed with the vapor of chloroform in exactly those proportions which give the best effect. The gas may be taken from two separate taps, or from a tube with a by-pass; one-half of the gas to be burnt goes through a bottle containing sponge saturated with chloroform. The outlet tube from the bottle is joined to one end of a λ piece; the gas is joined to the other; while a single tube goes to the burner. By regulating the two taps, the most brilliant spectra may be made to continue for several hours without trouble; and the spectra may be photographed.

On measuring spectra.—In making observations of the visible spectrum, measurements made with cross-wires in the eye-piece of the telescope are seldom quite concordant when series of measurements are made throughout the whole spectrum, first in one direction and then in the other; the differences are greater in the measurements of bands than in those of lines. This is due to two causes, the one, an alteration in the focus of the eye; the second, slight variations in the width and intensity of the bands. To counteract the first difficulty I have had two instruments made with graduated draw-tubes, and have marked the focus as determined for red, yellow, green, blue, and violet lines, such as lines of potassium, lithium, sodium, thallium, strontium, calcium, and a spark-line of magnesium. Of course the focusing is adapted to only one eye-piece. In measuring green rays the telescope is adjusted for the thallium line as marked upon the scale; and other measurements are easily made on either side of this. Each observer must focus for himself. In the measurements of bands the Mecke burner offers a decided advantage over the ordinary Bunsen flame, because it is not subject to fluctuations in temperature, and is on the whole hotter, being about 1400° C. throughout the body of the flame; the bands are therefore of uniform brilliancy and width. But, above all, the bands may be photographed, so that with the same photographic plates and the same exposure a similar spectrum is obtained, which can be measured by applying an ivory scale divided into hundredths of an inch, or fourths of a millimeter; and measurements may be repeated and corrected. Eye-observations record the average effect of brilliancy and intensity of lines and bands; while photographs are a record of the aggregate effect over a given period of time. All difficulties arising out of

inequality in sensitiveness of the prepared film to different colors are now overcome by the use of Wratten and Wainwright's panchromatic plates. The examples of flame-spectra of the calcium, strontium, and barium group show that, with a constant exposure, the width of the bands increases with the quantity of substance in the flame; with a constant quantity of substance and varying exposures, the width and intensity of the bands increase with the exposure. With certain elements the bands are widened and intensified more on the less refrangible side; with others, on the more refrangible. This explains what has been remarked by von der Seipen,[1] namely, that, between his measurements of the bands of metallic tin and mine, there is a large though constant difference in the wave-length values; and he attributes this to the old normal wave-lengths of Ångström being used. The difference, however, between the two sets of measurements amounts to from 4 to 7 Ångström units, but over the same range of spectrum the maximum difference between Hartley and Adeney's wave-lengths (1884) and Rowland's (1893)[2] is, at most, +1.1 Å unit, the minimum being +0.4, and the average something less than +0.8.

There is no doubt that my spectrum was photographed from a much larger quantity of material; and the exposure was also longer; and therefore the bands were broader and more intense.

[1] "Ueber das Flammenspektrum des Zinns," *Zeitschrift für wissenschaftliche Photographie*, 5, 69–85, 1907.

[2] J. F. Eder, "Beiträge zur Spectralanalyse," *K. K. Akad. Wissensch.*, Vienna, 60, 13, 1893.

A SUGGESTION TOWARD THE EXPLANATION OF SHORT-PERIOD VARIABILITY

By F. H. LOUD

Mr. Ralph H. Curtiss, in the *Astrophysical Journal* (20, 186, 1904), remarks, "It is easy to construct a plausible explanation for the light- and velocity-curves of *W Sagittarii* on the assumption that the system is pervaded by a resisting medium which enhances the brightness of that side of the star which faces the direction of motion. . . . . Until more data are available, it would be premature to follow out such theories."

The hypothesis as to the cause of short-period variability, which is here applied to a single star, having independently occurred to me—as no doubt to many others, and perhaps to some before Mr. Curtiss—I was looking through the *Astrophysical Journal* for data bearing upon its verification, when I came upon the above sentence. I desire to discuss briefly the conformity of the hypothesis with known facts, a few of them later in date of publication than the article above quoted.

It should first be observed that the special feature of *W Sagittarii* which appears to have prompted Mr. Curtiss' remark was the discovery that the light- and velocity-curves of this star are so related that approach to the earth is accompanied by brilliancy above the average, and recession from it by comparative faintness; this relation holding true not merely in a normal elliptical motion, but throughout a remarkable disturbance of the latter which characterizes this individual orbit, thus indicating that the star is bright or faint according as its advancing front is presented or not to our view.

A recent collection of all the instances, ten in number, in which the light- and velocity-curves of variables of this class have been examined, made by Mr. Sebastian Albrecht in the course of his original discussion[1] of two of them, has brought out the notable fact that this relation between approach and brilliancy holds good throughout the list and is apparently characteristic of the δ *Cephei* type of variables. This fact, due to Dr. Albrecht's own research, of course immensely strengthens the validity of the assumed cause, to which, however,

[1] *Lick Observatory Bulletin*, No. 118, p. 138; *Astrophysical Journal*, 25, 330, 1907.

the memoir of this astronomer makes no allusion. But the decisive test of the hypothesis must lie in its ability to account for the phenomena which characterize these variables as a class.

Of these, one of the most noteworthy is the rapid rise of the light-curve before maximum, followed by a decline which occupies, on the average, double the time of increase, and often much more. A few instances in which this peculiarity was deemed to be replaced by symmetry have been erected on that ground by some authorities into a separate species, having ζ *Geminorum* for a type. But it is doubtful whether a satisfactory instance of actual symmetry exists.

In the case of ζ *Geminorum* itself, the bisection of the period by the extreme phases, though very approximate, is not exact; while a secondary fluctuation of light preceding the principal maximum, and partially harmonizing with the disturbance of velocity discovered by Campbell, was reported by F. P. McDermott.[1]

In *U Vulpeculae*, too, the equality at first claimed is contested, and if the regularity of *RR Centauri* is as yet unimpeached, it would be hazardous to predict that it will remain so. On the other hand, the usual asymmetry is in no way fixed in degree, varying in sundry instances much below the mean; thus in *W Virginis* the time of increase is to that of decrease as 46 to 54; while *S Antliae*, according to Professor E. C. Pickering, exhibits a corresponding ratio of 62 to 38, thus for once overpassing the limit of symmetry. These stars must then be regarded, at least provisionally, as merely aberrant members of the class represented by δ *Cephei*.

On the other hand, the type represented by β *Lyrae* is entirely distinct. In the latter the maxima do not coincide with the times of most rapid approach; moreover, the character of the spectrum is clearly Sirian, while the variables of the class here considered are without exception either solar, or still farther removed from the Sirian type.[2] I do not propose in this paper to enter upon the dis-

[1] *Astrophysical Journal*, 16, 117, 1902.

[2] Of the 81 variables referred to Class IV in Miss Cannon's "Second Catalogue of Variable Stars" (*Annals H. C. O.*, 55, Part I), when the β *Lyrae* stars, with *U Leporis*, have been removed, as well as those whose spectra have not been satisfactorily examined, there remain 45, classified spectroscopically as follows: *F*, 6; *F2G*, 1; *F5G*, 6; *F8G*, 1; peculiar, but between *F* and *G*, 1; *G*, 12; *G5K*, 7; *K*, 4; *K5M*, 5; spectra continuous or nearly so, 2.

cussion of the cluster-type of variables, to which the name Antalgol has been applied by Hartwig. Of the isolated stars, like *Y Lyrae*, which conform to this type, none (unless *U Leporis*, which is Sirian, be classed among them) is of sufficient brightness to have yet permitted a satisfactory determination of its spectroscopic species, much less to afford a velocity-curve; and in the absence of the latter no theory of light-change can be verified.

The best-known and most representative stars of the class under discussion, are then, stars of advanced development, and at the same time binaries of short period, in which as a rule one component only of the pair is luminous, for the spectral lines undergo no periodic duplication. According to the hypothesis to be tested, this component owes its light to the resistance of a diffused medium, to which the other must be assumed to be relatively at rest. The visible star, then, is the satellite; and at so short a distance from the primary, the tides necessarily induced tend to impose upon it a rotation of equal rate with its revolution. The orbital movement, however, in parting with the energy which becomes the source of the star's visibility, is continually drawn into narrower compass, and thus accelerated in speed. The tidal action tends to restore the equality of the periods, with the result that the rotation is always a little—but only a little—slower than the revolution. The effect of this lag is that the area on the satellite, heated to brilliant incandescence, is of an unsymmetrical form. The point of greatest heating, since it occupies the momentary center of the advancing front, moves in consequence slowly around the equator, always entering upon regions comparatively cool, and drawing behind it regions glowing from their recent exposure to heat. Thus, as the revolution brings these regions successively into the line of sight, there appears first, to our view, a sudden rise of brightness, then, after the maximum, a long and gradual decline. The degree of cohesion in the surface, implied in this account, might well be too great for a star of Sirian tenuity, but not for the class of bodies actually concerned; especially if it be considered that both primary and satellite are presumed to have advanced far in condensation, with accompanying loss of light, the latter body being probably as dark as the former, save for the surface action of the resistance.

Exceptional cases of the disappearance or reversal of the usual asymmetry would occur if the rate of rotation should be equal to that of revolution, or more rapid—a condition which certainly might now and then be present, from various conceivable causes.

It seems quite in accordance with the hypothesis under consideration that the maxima, depending as above upon the visibility of a highly heated region, should show a special accentuation of the light of short wave-length; and both Albrecht and Wilkens find this to be distinctly the case.

On the other hand, an objection is apparent in the fact that the moment of most rapid approach to the earth, which might be expected from the hypothesis to occur—if on either side—a little before the maximum of brilliancy, appears from the published measurements to come more commonly after it. In the type-star, indeed, δ *Cephei*, and also in *T Vulpeculae*, one of the stars examined by Mr. Albrecht, the expected relation is confirmed by observation, but in seven others the contrary holds. The discrepancy between the times of extreme phase in the curves of light and velocity is in no case large, but varies from zero to nearly 8 per cent. of the period, which is its value in *Y Ophiuchi*, the other of Mr. Albrecht's stars. As the period of this star is unusually long, the mean interval amounts in this case to a day and three-tenths; and the observations leave little doubt of the reality of the phenomenon. Its recognition, however, is not necessarily fatal to the hypothesis. One way of reconciling the latter to the fact might be to imagine that the impact of the nebulous particles upon the star induces an increase not only of heat but of general absorption; then the maximum brilliancy might precede the greatest frequency of impact in very much the same way as the maximum light of a Colorado summer day, in consequence of afternoon clouds, occurs a little before noon. If it be granted that, under such circumstances, the radiation of short period would be first to receive a check to its growing intensity, we may find a confirmation of this suggestion in the fact that the photographically determined light-maximum of *T Vulpeculae* appears from the measurements of Wilkens to precede by a perceptible interval that obtained from visual observations. In fact, if the time of light maximum deduced by this observer be accepted, this star no longer forms with δ *Cephei*

an exception to the prevailing rule of arrangement, but takes its place with the majority.

Another well-known but by no means constant feature of the light-curves of this class of variables is that described by Miss Clerke[1] as "an inherent tendency to a second maximum, sometimes barely indicated as a pause in descent, but in several cases giving rise to a pronounced 'hump' in the downward slope of the light-curve."

Secondary fluctuations in brightness, on the theory proposed, might be produced in at least three different ways:

a) The orbit, which has thus far been discussed as if it were circular, is in fact, of course, generally elliptical; and the epoch of periastron must be marked by more intense heat, due to greater velocity of motion.

b) The orbital eccentricity will occasion a libration[2] which will modify the above-mentioned lag of rotation. For instance, if it happen that the time of greatest negative velocity in the line of sight nearly coincides with that of apastron, the orbital movement, temporarily reduced in velocity, may perchance be of about equal speed with the rotation. This has been mentioned as the condition for symmetry in the light-curve, and the latter may accordingly present such an appearance at its summit, with a pronounced "hump" further on, where the gain of the revolution on the rotation has become marked.

c) The resisting particles, instead of forming a stationary and uniform medium, may have an unequal distribution or an independent motion. This third condition, it would appear, must prevail in instances like *T Monocerotis*, when the amplitude of variation is inconstant. Its consideration will, on the other hand, be excluded whenever—as in the greater number of stars—such a feature is absent.

Recurring to the other two specifications, (*a*) and (*b*), which are

[1] *Problems in Astrophysics*, p. 320.

[2] The term "libration"—here used by reason of its suggestiveness of the relation between the two movements—is perhaps not altogether appropriate, since the visibility of a particular point of the surface from an infinite distance depends, of course, on rotation alone. The actual effect of the varying rapidity of revolution will be to elongate the area of maximum heating at periastron and contract it at apastron, its forward movement on the surface being accelerated at the former aspect and checked at the latter.

both dependent upon the ellipticity of the orbit, it is to be remarked that the fact that their efficiency must combine in an unknown proportion will render difficult what would otherwise appear a promising test of the hypothesis, applicable in all cases in which the eccentricity and the position of the line of apsides is known from the curve of velocity. Together, they may well occasion, in some instances, two subordinate waves in the light-curve, which in other cases may be blended; nor should the three maxima be expected to conform to any easily distinguishable rule as to their distribution through the period.

Colorado College
August 30, 1907

THE EFFECT OF PRESSURE UPON ARC SPECTRA[1] NO. I.—IRON

By W. GEOFFREY DUFFIELD

The first part of the paper contains a description of the mounting and adjustment of the large Rowland concave grating in the Physical Laboratory of the Manchester University. The feature of this is the stability of the carriages carrying the grating and camera, and the novel construction and attachment of the cross-beam, which secure the absence of any disturbance which might be caused by bending or sagging.

The second part describes experiments made with a pressure cylinder designed by Mr. J. E. Petavel, in which an arc is formed between metal poles opposite a glass window, through which the light is examined by means of the grating spectroscope. A system of mirrors allows the image of the arc, however unsteady it may be, to be kept almost continuously in focus upon the slit.

Two sets of photographs of the iron arc in air have been taken for pressures ranging from 1 to 101 atmospheres (absolute), and the results are given below for wave-lengths $\lambda = 4000$ Å.U. to $\lambda = 4500$ Å.U.

I. BROADENING

1. With increase of pressure all lines become broader.

2. The amount of broadening is different for different lines, some almost becoming bands at high pressures, and others remaining comparatively sharp.

3. The broadening may be symmetrical or unsymmetrical; in the latter case the broadening is greater on the red side.

II. DISPLACEMENT

1. Under pressure the most intense portion of every line is displaced from the position it occupies at a pressure of 1 atmosphere.

2. Reversed as well as bright lines are displaced.

[1] Abstract of a paper communicated by Professor A. Schuster to the Royal Society, July 4, 1907.

3. With increase of pressure the displacement is toward the red side of the spectrum.

4. The displacement is real and is not due to unsymmetrical broadening.

5. The displacements are different for different lines.

6. The lines of the iron arc can be grouped into series according to the amounts of their displacements.

7. Three groups can in this way be distinguished from one another; the displacements of Groups I, II, III bear to one another the approximate ratio 1:2:4. (The existence of a fourth group is suggested by the behavior of two lines, but further evidence is needed upon this point; 1:2:4:8 would be the approximate relations existing between the four groups.)

8. Though all the lines examined, with two possible exceptions, fall into one or other of these groups, the lines belonging to any one group differ to an appreciable extent among themselves in the amounts of their displacements.

9. The relation between the pressure and the displacement is in general a linear one, but some photographs taken at 15, 20, and 25 atmospheres pressure give readings incompatible with this relation. Other photographs at 15 and 25 atmospheres present values which are compatible with it.

10. The abnormal readings are approximately twice those required by the displacements at other pressures, if the displacement is to be a continuous and linear function of the pressure throughout.

11. On the photographs showing abnormal displacements the reversals are more numerous and broader than they are on plates giving normal values, and there is some evidence in favor of a connection between the occurrence of abnormal displacements and the tendency of the lines to reverse.

III. REVERSAL

1. As the pressure is increased, reversals at first become more numerous and broader.

2. The tendency of the lines to reverse reaches a maximum in the neighborhood of 20 to 25 atmospheres, and a further increase in pressure reduces their number and width.

3. Two types of reversal appear on the photographs, symmetrical and unsymmetrical.

4. Within the range of pressure investigated, the reversals show no tendency to change their type.

5. In the case of unsymmetrically reversed lines in the electric arc, the reversed portion does not in general correspond to the most intense part of the emission line, being usually on its more refrangible side.

6. The displacements of the reversed parts of the unsymmetrically reversed lines of Group III are about one-half the displacements of the corresponding emission lines. Indeed, the reversed parts of the lines of Group III fall approximately in Group II.

7. No relation between the order of reversal and the frequency of vibration, such as exists in the spark, has been observed in the iron arc for the ranges of wave-length and pressure examined.

IV. INTENSITY

1. The intensity of the light emitted by the iron arc is, under high pressures, much greater than at normal atmospheric pressure.

2. Changes in relative intensity of the lines are produced by pressure. Lists of enhanced and weakened lines are given.

Reviews

A REDETERMINATION OF THE LENGTH OF THE METER IN TERMS OF THE WAVE-LENGTH OF THE RED CADMIUM LINE

In the issue of *Comptes Rendus* for May 21, 1907 (**144**, 1082–1086), Messrs. Benoit, Fabry, and Perot briefly state the results of this work, which they have been conducting at the laboratory of the Conservatoire des Arts et Métiers. The highly satisfactory outcome is that the earlier determination by Michelson, made at the International Bureau of Weights and Measures in 1892–93, with the collaboration of the bureau, is confirmed within less than one ten-millionth part. In view of the fundamental importance of the matter in spectroscopy, we give here an abstract of the paper.

The mean from three independent determinations by Michelson, by the interference methods he devised, was inferred from their accordance to have a precision of about one half-millionth, which would now seem to have been an underestimate.

Researches by Messrs. Perot and Fabry on interference produced with silver films had led them to new methods which seem superior to the earlier procedure in ease, rapidity, and precision. Accordingly the International Committee on Weights and Measures added to their programme a new measurement of the meter in terms of wave-lengths, in collaboration with Messrs. Perot and Fabry. In the meantime the adoption by the Internationnational Union for Solar Research of the wave-length of the red cadmium line as the basis for spectroscopic measurements increased the importance of the work.

Two operations are involved: (1) the exact determination of the number of wave-lengths and fractions of a wave-length contained in a bar about one meter long; (2) a comparison of this bar with the international prototype.

The bar was of invar, U-shaped in section, 5 cm square on the outside with an interior space 3x3 cm through which a beam of light could be passed; at the ends of the bar parallel silver-on-glass mirrors were attached in the manner previously used by Fabry and Perot. Lines were traced on the upper faces of the mirrors, very close to the edge from which two could be chosen separated by very nearly one meter; this distance was the one measured in wave-lengths.

It was not possible to determine directly the whole number of waves, n (3,103,800), as interference cannot be produced with such a large difference

of path, so that an intermediate standard of length 6.25 cm was selected, which was measured in terms of wave-lengths, and then compared optically with a standard of about twice its length, and so on until the comparison was made for the entire length of one meter. In so doing, the standards were placed one behind the other with their axes in line. The two thin plates serving as compensators were placed at one side and one set of the mirrors permitted us to pass the light at will through any two standards in discussion, and through a thin plate. The order of operations was as follows: the determination of the order of interference in red cadmium of the 6.25 cm standard by observation of the coincidences of red and green, and measurement of the diameter of the first red ring visible; successive comparisons with two thin plates, standardized at the same moment, of each standard with the double of the preceding standard, i. e., (2×6.25 cm) with 12.5 cm; (2×12.5) with 25 cm; (2×25) with 50 cm; (2×50) with 100 cm.

The same measures were then made in inverse order to eliminate the influence of a change in each standard between the time of its comparison with the preceding and with the following standard due to any barometric variation—the variations of temperature being practically negligible since the expansion of invar almost exactly neutralizes that of the air.

The measure of the number of wave-lengths n contained in the sum of the distances separating the lines selected on the faces of the plates which terminated the standard of 10 cm, was made by so mounting the plates successively on two standards of about 1 cm and 2 cm that the distances between the marks in the one case should be double that of the other; the distance between the plates on the 2-cm standard less twice that between the plates when mounted on the 1-cm standard will give the length sought for. In practice similar standards can only be approximated, and we accordingly proceeded as follows:

All the dimensions being expressed in wave-lengths, let E and E' be the distances between the plates, D and D' the distances between the marks, in the two standards and let n be the number sought, then

$$D=E+n\,, \qquad D'=E'+n\,.$$

The standard was so constructed that D' differed very little from $2D$. An invar bar was then made with marks sensibly equi-distant, the distance between any two consecutive marks closely approximating D. Consider now three of these marks, which define two intervals, d and d'. By means of a longitudinal comparator the nearly equal lengths D and d, D and d', D' and $d+d'$ are compared and the following equations obtained:

$$\begin{aligned} E+n&=d+e\,, \\ E+n&=d'+e'\,, \\ E'+n&=d+d'+e''\,. \end{aligned}$$

The very small quantities e, e', e'', are given in microns by measurement with the comparator and reduced to wave-lengths; E and E' are measured optically. By eliminating d and d' we obtain n. In practice, six intervals were used instead of two. The number of equations was then greater than the number of unknowns and they were solved by the method of least squares.

From a series of fifteen measures carried over six intervals the number was found to be 1270.95 wave-lengths of the red ray or 0.81830 mm.

The comparison of the meter with the distance between the marks on the glass plates carried by the 100-cm standard was made at the same time with the optical measures by comparison with a bar drawn from the same ingot of metal, specially constructed, and investigated with the greatest care by the International Bureau of Weights and Measures relatively to the principal standards in use. Its length differed in the month of November by 4μ from that of the meter, and it lengthened in two months (October to December 1906) by only $0.12\ \mu$.

With the wave-lengths reduced to dry air at 760 mm pressure and 15° on the scale of a hydrogen thermometer, the results of the four optical series utilized, out of the seven made, were as follows:

Series 3..........	1 meter = 1,553,164.12,	$\lambda = 0^{\mu}.64384696$
4..........	.16	695
7..........	.22	692
5..........	.02	700
Mean,	1 meter = 1,553,164.13,	$\lambda = 0.64384696$

The mean of the entire seven series, of which three should apparently be set aside is

$$1 \text{ meter} = 1{,}553{,}163.99\,, \qquad \lambda = 0^{\mu}.64384702\,.$$

It is interesting to note the close accordance of these figures with those of Michelson and Benoit, obtained fourteen years earlier. If their values are reduced to a temperature of 15° (hydrogen scale) and to zero humidity (by applying a plausible but somewhat uncertain correction, which was not done at the time), the result is

$$\lambda = 0^{\mu}.64384700\,,$$

as the mean of three measures having a range of sixty-seven units of the last place. Hence the present measures differ from the earlier ones by less than a ten-millionth part of their relative value. Whatever element of chance there may be in this extraordinary agreement, it is obvious that the prototype meter has not varied in the last fourteen years.

NOTICE

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

In the department of *Minor Contributions and Notes* shorter articles will generally be placed and subjects may be discussed which belong to other closely related fields of investigation.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right, unless the author requests that the reverse procedure be followed.

Accuracy in the proof is gained by having manuscripts type-written, provided the author carefully examines the sheets and eliminates any errors introduced by the stenographer. It is suggested that the author should retain a carbon or tissue copy of the manuscript, as it is generally necessary to keep the original manuscript at the editorial office until the article is printed.

All drawings should be carefully made with India ink on stiff paper, usually each on a separate sheet, on about double the scale of the engraving desired. Lettering of diagrams will be done in type around the margins of the cut where feasible. Otherwise printed letters should be put in lightly with pencil, to be later impressed with type at the editorial office, or should be pasted on the drawing where required.

Authors will please carefully follow the style of this *Journal* in regard to footnotes and references to journals and society publications.

Authors are particularly requested to employ uniformly the metric units of length and mass; the English equivalents may be added if desired.

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ERRATA

Astrophysical Journal, Vol. 24, December 1906, in Mr. Very's article on "The Temperature of the Moon":

Page 351, fourth line, *for* only, *read* mainly.

Astrophysical Journal, Vol. 25, June 1907, in Mr. Ichinohe's article on the "Orbit of the Spectroscopic Binary κ *Cancri*":

Page 317, next to last line, *for* 3.393, *read* 6.393.

Page 318, third line, *for* 3.393, *read* 6.393.

Astrophysical Journal, Vol. 25, June 1907, in Mr. Ludendorff's article on the "Orbit of the Spectroscopic Binary β *Arietis*":

Page 320, line 16, *for* 32, *read* 321.

Page 321, line 21, *for* which gave values, *read* for which λ 4481 and $H\gamma$ gave values.

Page 324, last line, *for* -7.2, *read* -7.0.

Page 327, sixth line from foot, *for* mean value, *read* mean error.

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SUBJECTS

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AUTHORS

John Collier pinxt

SIR WILLIAM HUGGINS

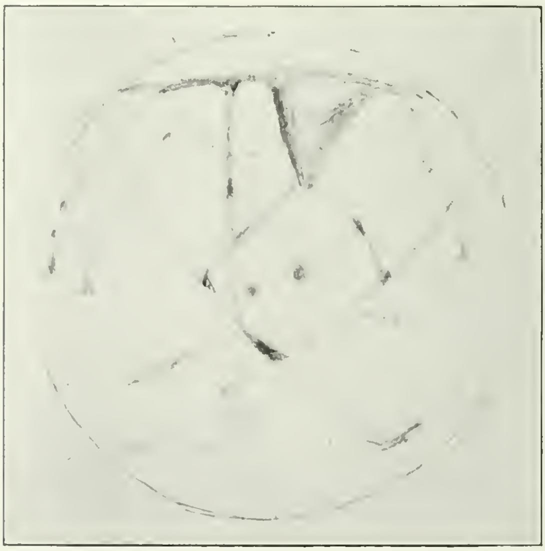
PLATE I

WASH DRAWING BY AUTHOR
Reduced from a diameter of 38 cm

PLATE III

SKETCHES

By E. E. Barnard
With Naked Eye from 95 feet



By Philip Fox
With Naked Eye from 96 feet

PLATE II

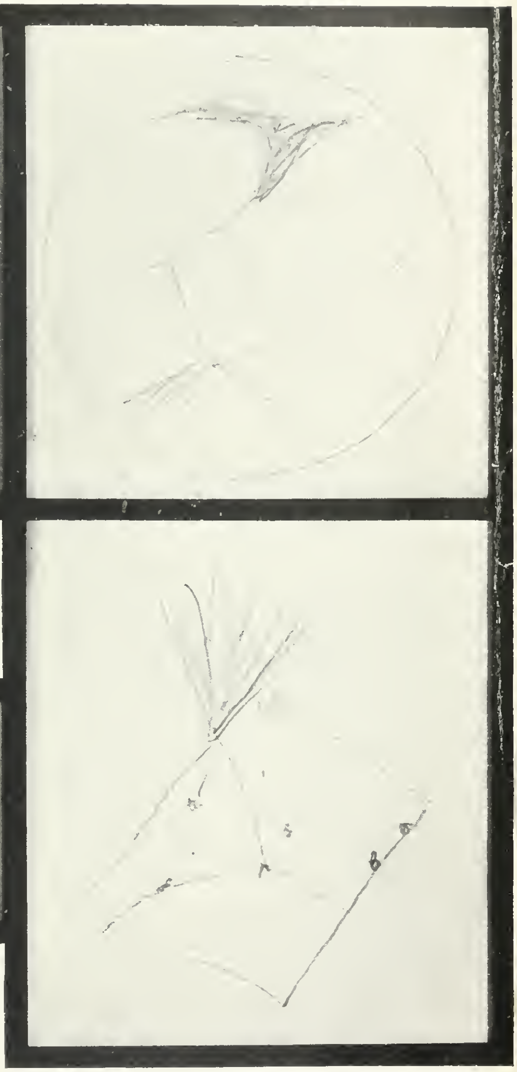
SKETCHES

By S. I. Bailey

Naked Eye from 100 feet

Detail of lower part: Opera-glass, power of 2 from 100 feet

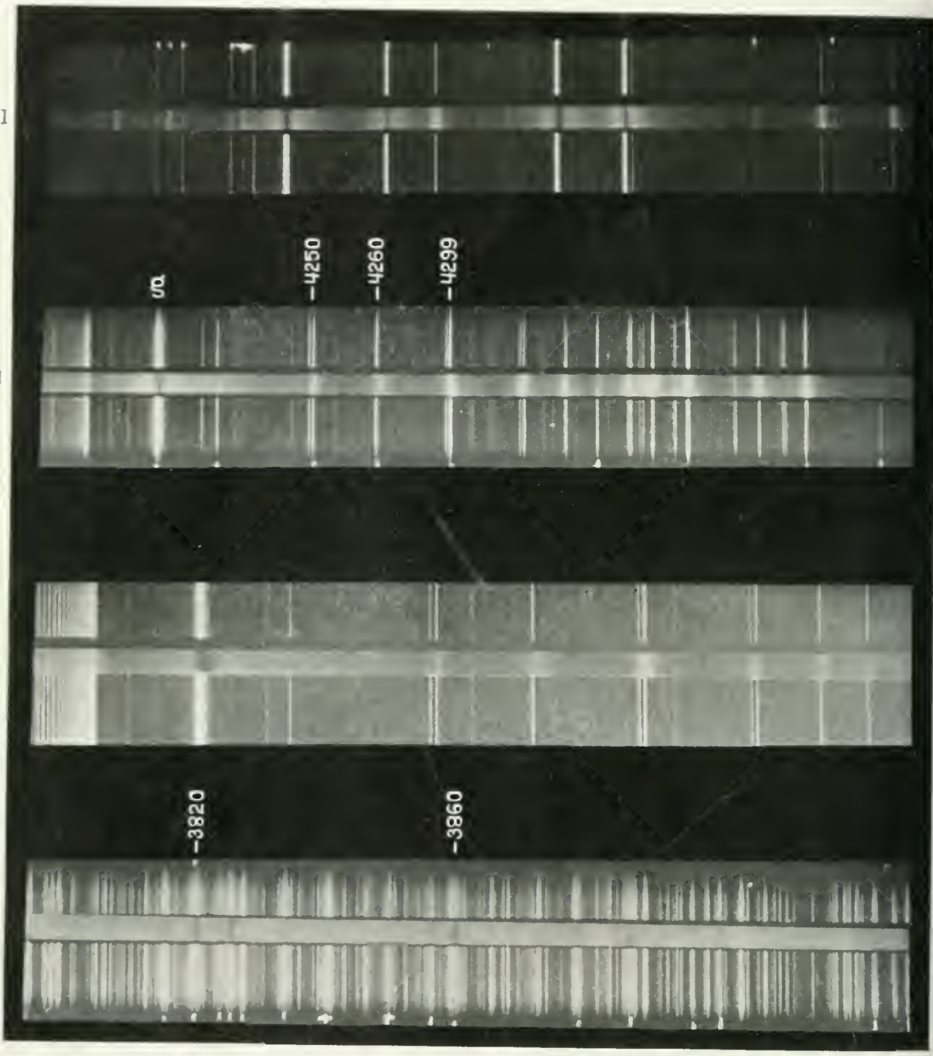
By W. H. Pickering



The upper Sketch with Naked Eye from 30 meters. The lower, detail with opera-glass from 100 feet

PLATE IV

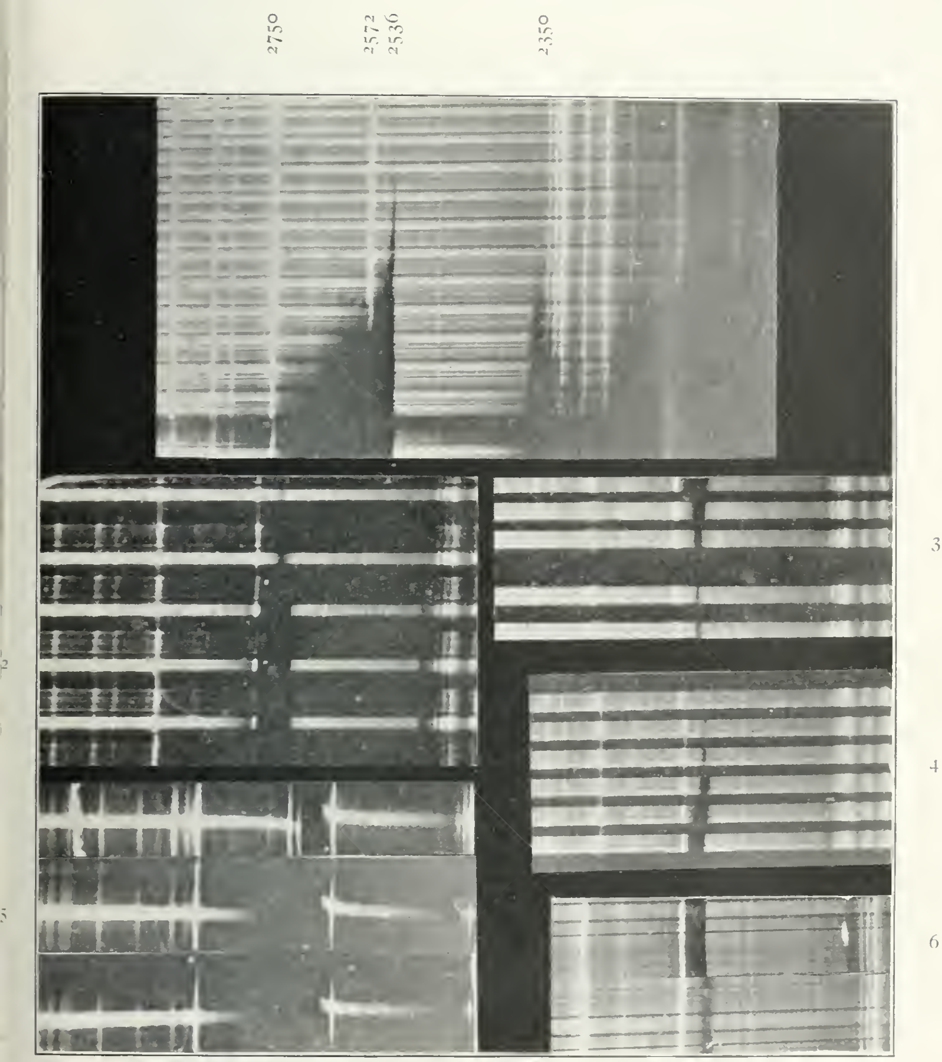
K H



I
II
III
IV

ARC SPECTRA UNDER HEAVY PRESSURE

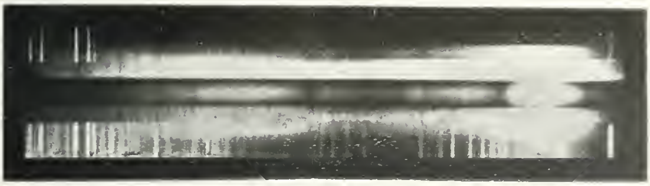
PLATE V



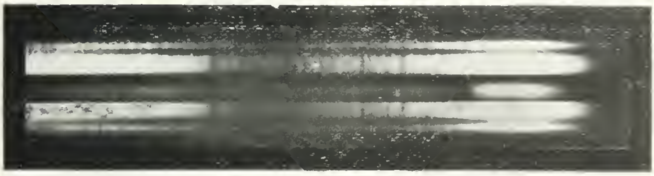
Absorption Spectra of Mercury Showing Influence of Foreign Gas on Appearance of Absorption Band

PLATE VI

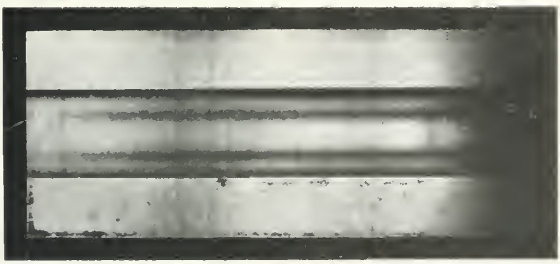
NEPTUNE



URANUS



SATURN



JUPITER

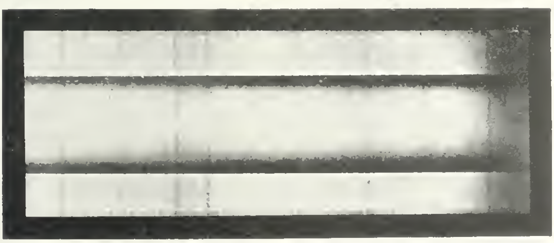


PLATE VII

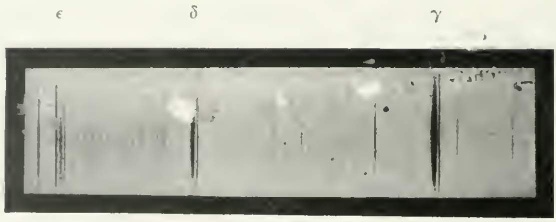


FIG. 1.— Canal Rays in Hydrogen

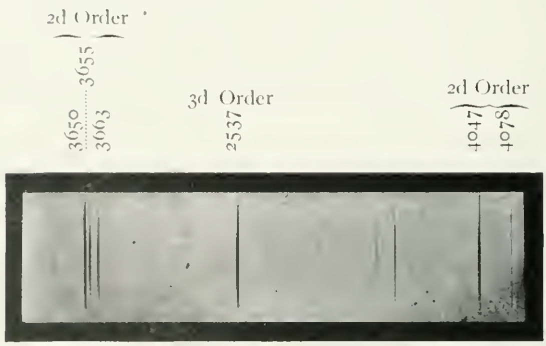


FIG. 2.— Canal Rays in Mercury Vapor

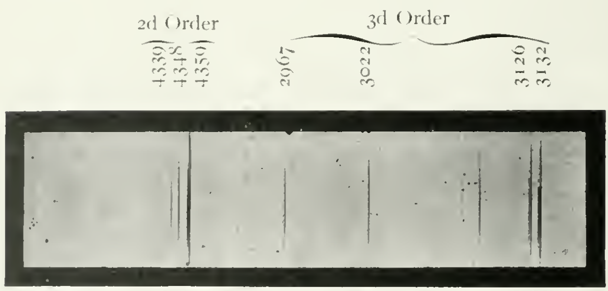


FIG. 3.— Canal Rays in Mercury Vapor

PLATE VIII

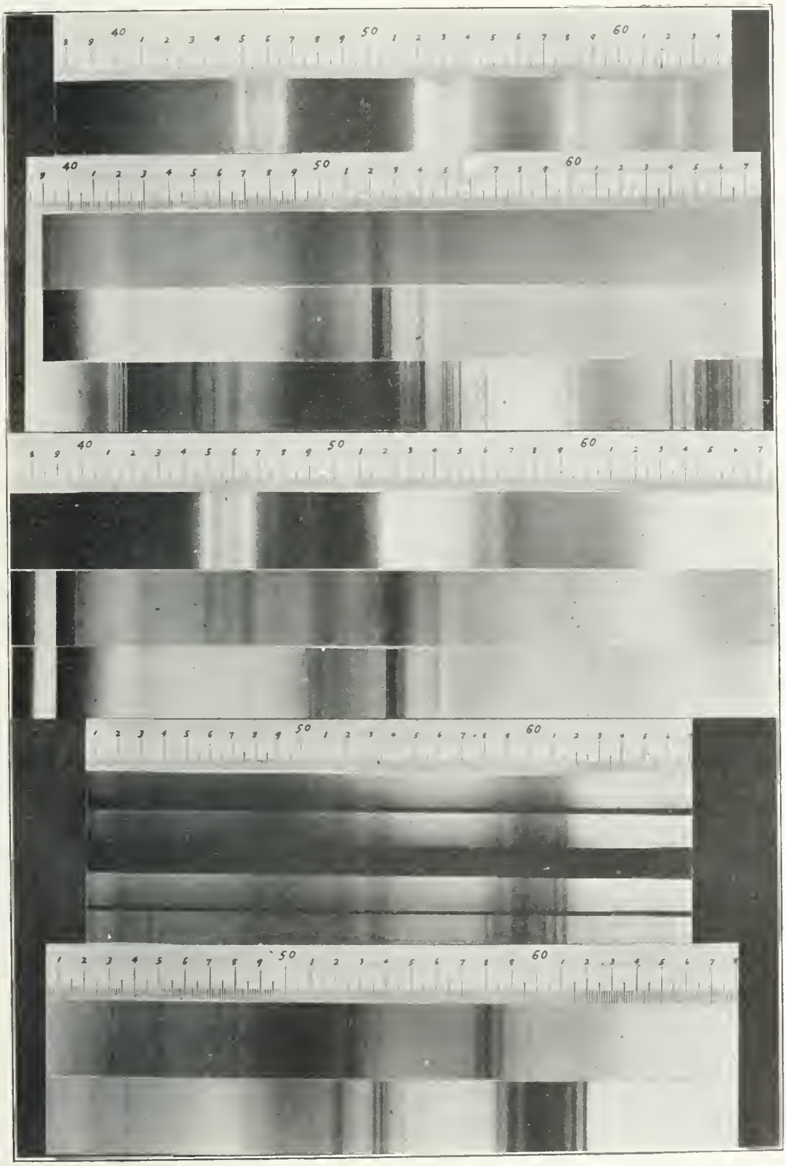


FIG 3

FIG 4 a b c

FIG 5. a b c

FIG 6 4 3 2 1

FIG 7

PLATE IX

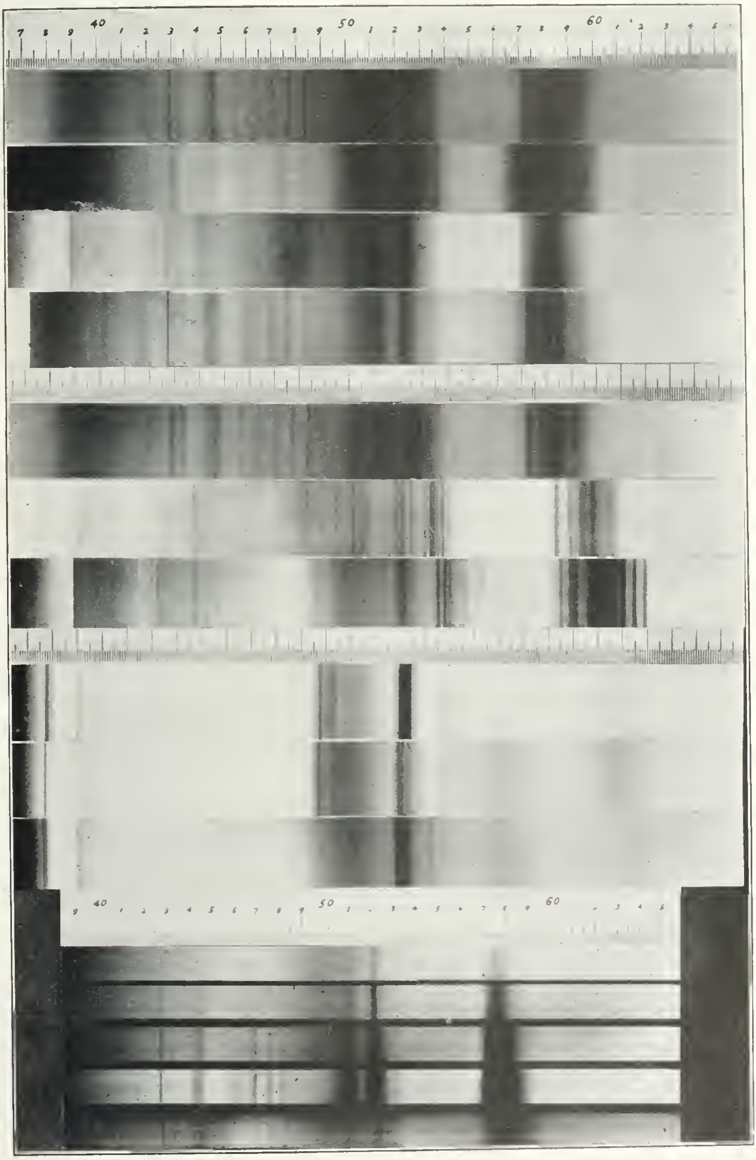


FIG 8

FIG. 9.

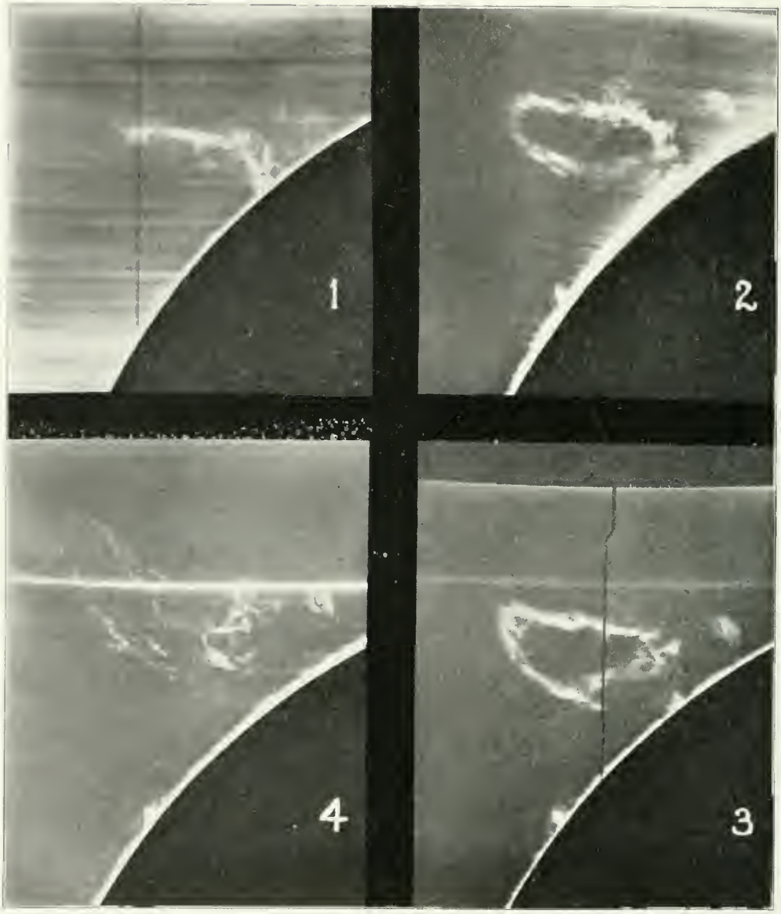
FIG 10.

FIG 11.

PLATE X

S

E



W

Eruptive Prominence, May 21, 1907
Photographed with the Rumford Spectroheliograph.

PLATE XI

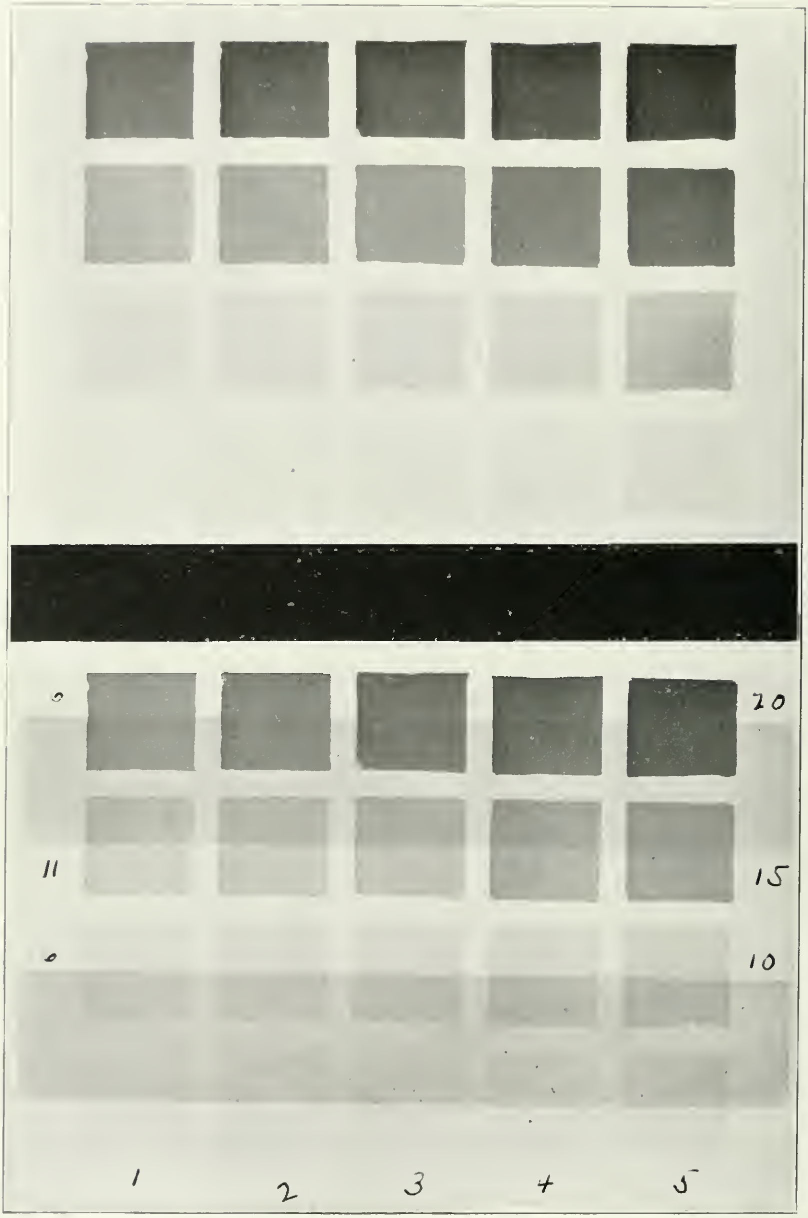
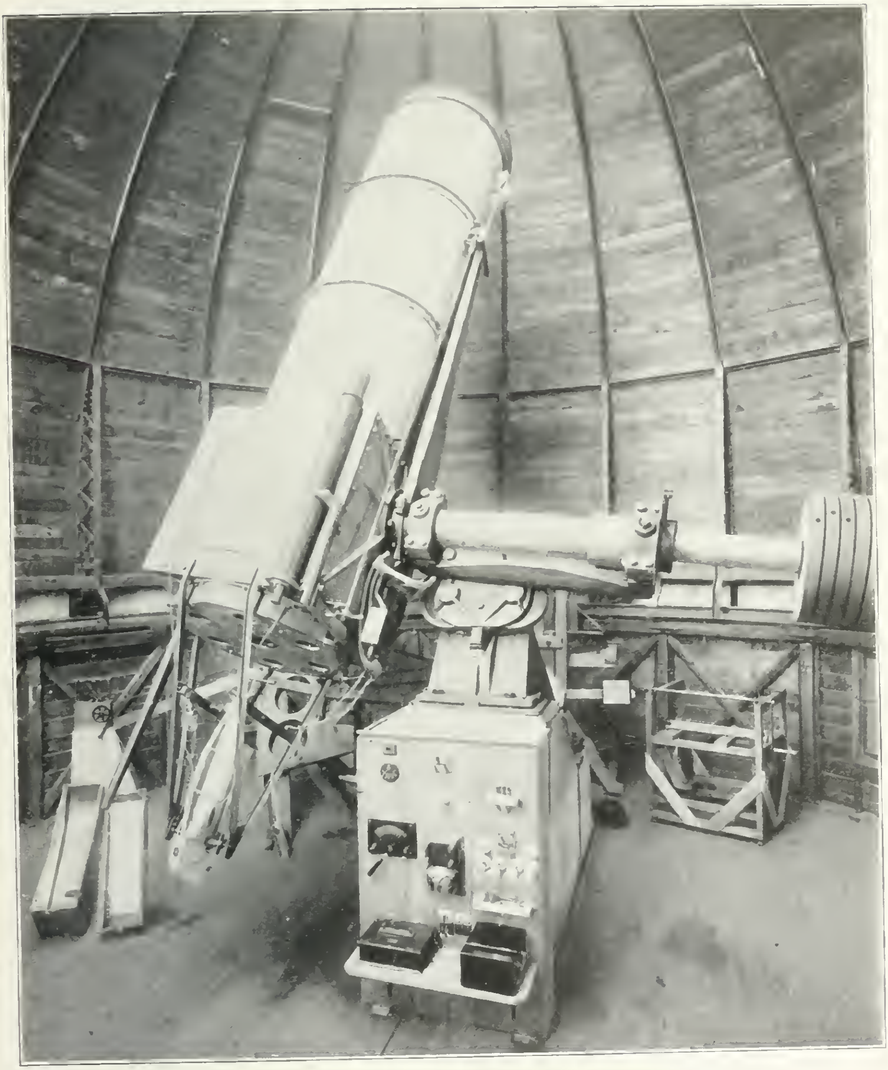


Fig. 2

Fig. 3

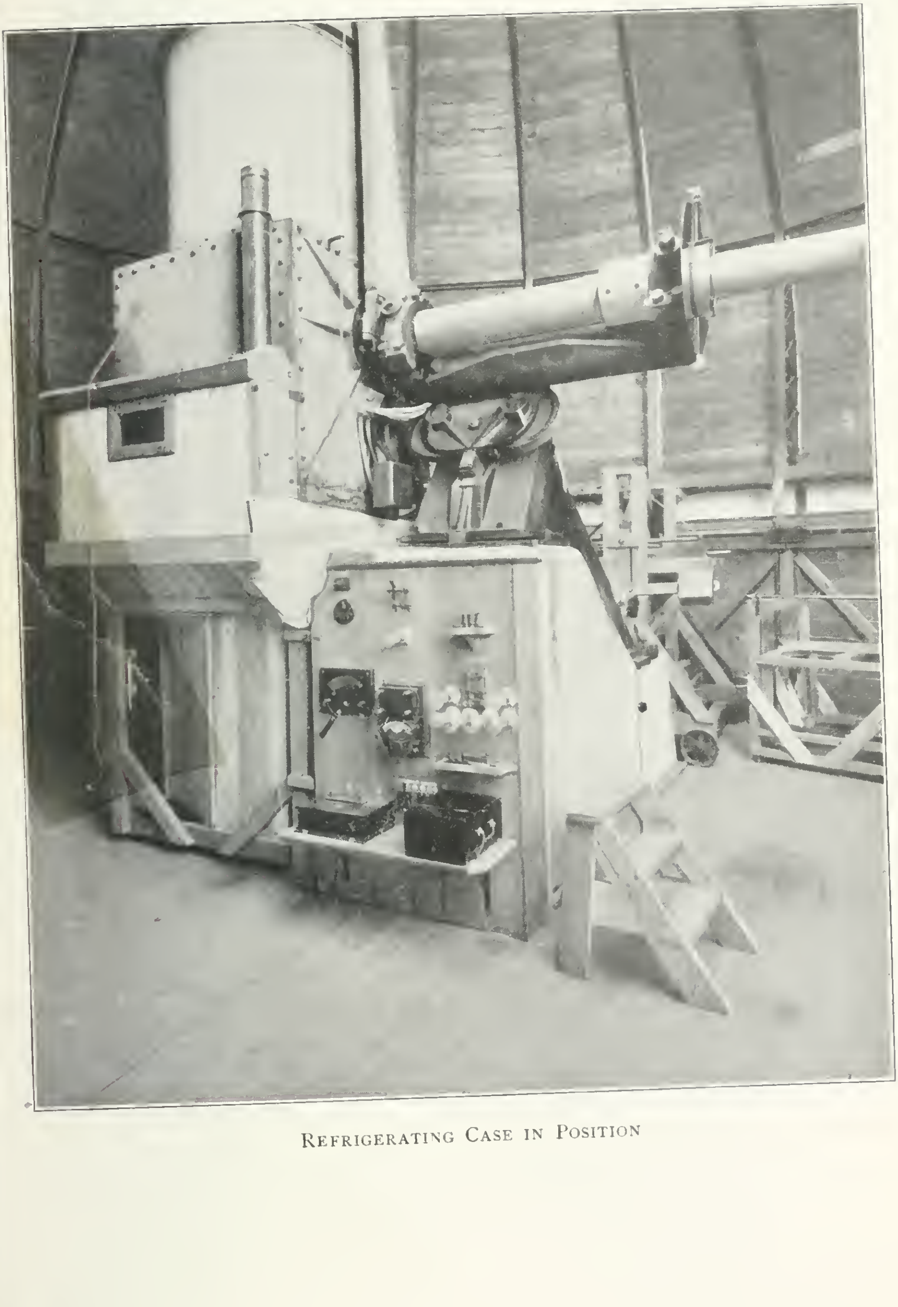
Sensitometer Plates

PLATE XII



THE REFLECTING TELESCOPE AND THREE-PRISM SPECTROGRAPH OF THE D. O. MILLS EXPEDITION

PLATE XIII



Refrigerating Case in Position